Lecture notes on physics of plasma

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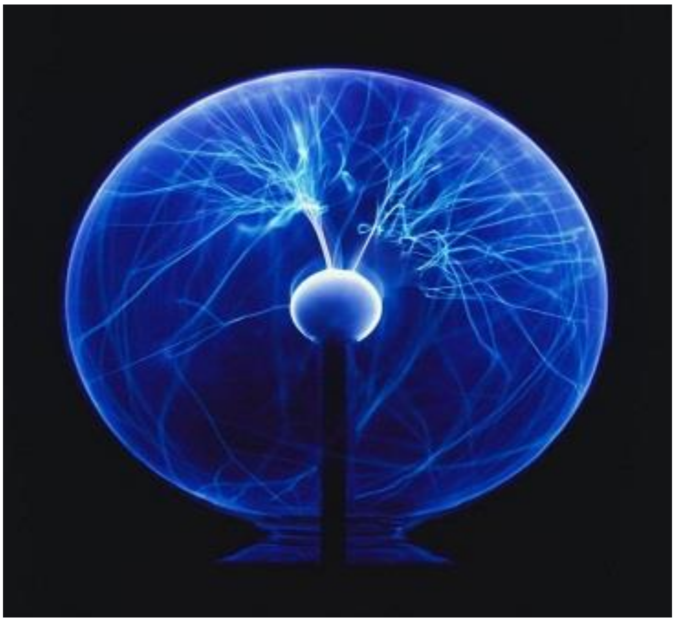


Contents

1.1 Definition of Plasma

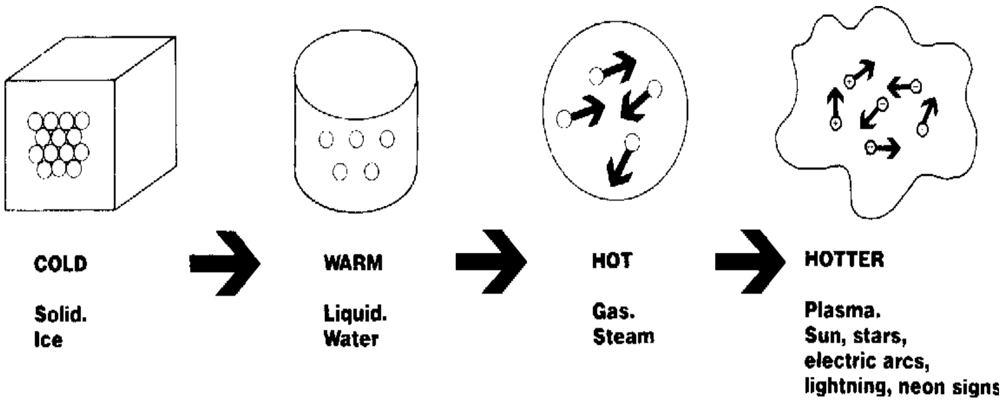
The word plasma is used to describe a wide variety of macroscopically neutral substances containing many interacting free electrons and ionized atoms or molecules, which exhibit collective behavior due to the long-range coulomb forces. Not all media containing charged particles, however, can be classified as plasmas. For a collection of interacting charged and neutral particles to exhibit plasma behavior, it must satisfy certain conditions, or criteria, for plasma existence. The word plasma comes from Greek and means something molded. It was applied for the first time by Tonks and Langmuir, in 1929, to describe the inner region, remote from the boundaries, of a glowing ionized gas produced by electric discharge in a tube, the ionized gas as a whole remaining electrically neutral.

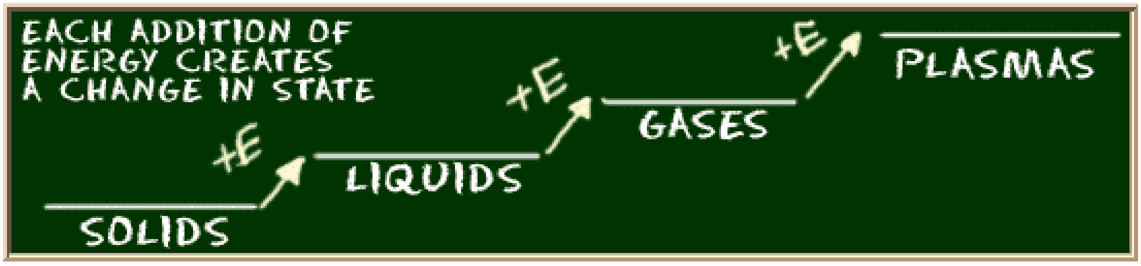
Where is plasma?

The visible Universe is 99.999% plasma. The Sun is about 100% plasma, as are all stars. Plasma makes up nearly 100% of the interplanetary, interstellar and intergalactic medium. The Earth's ionosphere is plasma.

1.2 Plasma as the Fourth State of Matter

From a scientific point of view, matter in the known universe is often classified in terms of four states: solid, liquid, gaseous, and plasma. The basic distinction among solids, liquids, and gases lies in the difference between the strength of the bonds that hold their constituent particles together. These binding forces are relatively strong in a solid, weak in a liquid, and essentially almost absent in the gaseous state. Whether a given substance is found in one of these states depends on the random kinetic energy (thermal energy) of its atoms or molecules, i.e., on its temperature The equilibrium between this particle thermal energy and the interparticle binding forces determines the state By heating a solid or liquid substance, the atoms or molecules acquire more thermal kinetic energy until they are able to overcome the binding potential energy. This leads to phase transitions, which occur at a constant temperature for a given pressure. The amount of energy required for the phase transition is called the latent heat If sufficient energy is provided, a molecular gas will gradually dissociate into an atomic gas as a result of collisions between those particles whose thermal kinetic energy exceeds the molecular binding energy At sufficiently elevated temperatures an increasing fraction of the atoms will possess enough kinetic energy to overcome, by collisions, the binding energy of the outermost orbital electrons, and an ionized gas or plasma results. However, this transition from a gas to plasma is not a phase transition in the thermodynamic sense, since it occurs gradually with increasing temperature





History of Plasma :

Plasma was first identified by Sir William Crookes in a Crookes tube in 1879 and he called it "radiant matter". Later in 1927 Irving Langmuir, the Nobel laureate who pioneered the scientific study of ionized gas, gave this new state of matter the name "Plasma"

1.3 Properties of plasma

➢ Properties: (i) Plasma is a state of matter in which an ionized gaseous substance becomes highly electrically conductive to the point that long-range electric and magnetic fields dominate the behaviour of the matter.

(ii) The plasma state can be contrasted with the other states: solid, liquid, and gas.

(iii) Plasma is an electrically neutral medium of unbound positive and negative particles (i.e. the overall charge of a plasma is roughly zero).

(iv) Moving charged particles generate an electric current within a magnetic field, and any movement of a charged plasma particle affects and is affected by the fields created by the other charges. In turn this governs collective behavior with many degrees of variation.

1.4 Classification of plasmas :

Depending on the degree of ionization (α) of the plasma it is classified as (i) Fully ionized plasma, (ii) Weakly ionized plasma and (iii) Partially ionized plasma. In fully ionized plasma assumed to have 100% ionization of the plasma gas, the Coulomb collisions play an important role over the binary interactions. In weakly ionized plasmas the binary interactions dominate over the Coulomb collisions. In partially ionized plasma, the binary interactions and Coulomb interactions are comparable in strength.

Plasma classification (types of plasma)

Cold plasma

There is a plasma composed of the same number of electrons and ions. In low pressure gas discharge, the collision rate between electrons and gas molecules is not frequent enough for non-thermal equilibrium to exist between the energy of the electrons and the gas molecules. So the high-energy particles are mostly composed of electrons while the energy of the gas molecules is around room temperature. We have Te >> Ti >> Tg where Te, Ti and Tg are the temperatures of the electron, ion and gas molecules, respectively. This type of plasma is called“cold plasma”.

Hot plasma

A hot plasma in one which approaches a state of local thermodynamic equilibrium (LTE). A hot plasma is also called a thermal plasma, but in Russian literature, a “low temperature” plasma in order to distinguish it from a thermonuclear fusion plasma. Such plasmas can be produced by atmospheric arcs, sparks and flames.

Warm plasma

Cold plasma (non-thermal plasma)

A cold plasma is one in which the thermal motion of the ions can be ignored. Consequently there is no pressure force, the magnetic force can be ignored, and only the electric force is considered to act on the particles. Examples of cold plasmas include the Earth’s ionopshere (about 1000K compared to the Earth’s ring current temperature of about 108K)., the flow discharge in a fluorescent tube

Ultracold plasma

An ultracold plasma is one which occurs at temperatures as low as 1K. and may be formed by photoionizing laser-cooled atoms. Ultracold plasmas tend to be rather delicate, experiments being carried out in vacuum.

Plasmas in Nature :

Though naturally occurring plasma is rare on earth, it is the most plentiful form of matter in the universe.

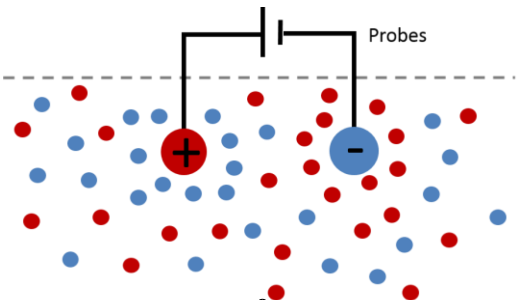
- *Plasma in space* :
  - Stars
  - Coronas
  - Solar wind
  - Star nurseries
  - Interstellar Nebulae
  - In the magnetic fields of many planets
  - Interplanetary, Interstellar and Intergalactic mediums
  - The accretion disks and accretion disk jets of black holes
  - Sun exists in 99.85% plasma state. The Sun is 1.5 million Km ball of plasma heated by Nuclear Fusion.
  - Space is not empty vacuum. It is actually filled with plasma that conducts our EM wave signals. OurUniverse is 99.9% Plasma.
- *Terrestrial Plasmas :*
  - Fire (When hotter than 1500°C)
  - Lightning
  - The magnetosphere
  - The ionosphere
  - The plasmasphere
  - The polar aurorae
  - The polar wind
  - Upper atmospheric lightning (e.g. Blue jets, Blue starters)
  - Sprites
- *Artificial Plasmas :*
  - Those found in plasma displays, including TV screen
  - Inside fluorescent lamps, neon signs
  - Rocket exhaust and ion thrusters

- ➢ The area in front of a spacecraft's heat shield during re-entry into the atmosphere
- ➢ Inside a corona discharge Ozone generator
- ➢ Fusion energy research
- ➢ The electric area in an arc lamp, an arc welder or plasma torch
- ➢ Plasma ball (Plasma sphere or Plasma globe)
- ➢ Arcs produced by Tesla coils
- ➢ Plasmas are used in semiconductor device fabrication
- ➢ Laser produced plasma
- ➢ Static electric sparks

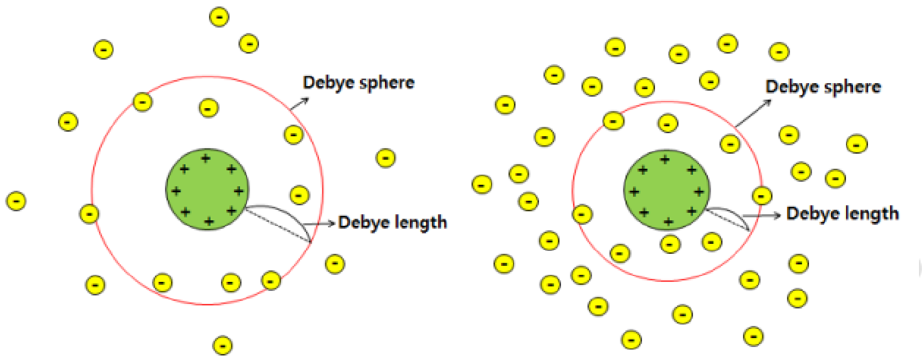
2.1Debye Shielding

In most types of plasma, quasi-neutrality is not just an ideal equilibrium state; it is a state that the plasma actively tries to achieve by readjusting the local charge distribution in response to a disturbance. Consider a hypothetical experiment in which a positively charged ball is immersed in plasma; see Figure below. After some time, the ions in the ball's vicinity will be repelled and the electrons will be attracted, leading to an altered average charge density in this region. It turns out that we can calculate the potential $\varphi(r)$ of this ball after such a readjustment has taken place.

Plasmas generally do not contain strong electric fields in their rest frames. The shielding of an external electric field from the interior of plasma can be



viewed as a result of high plasma conductivity: *i.e.*, plasma current generally flows freely enough to short out interior electric fields. However, it is more useful to consider the shielding as a *dielectric* phenomenon: *i.e.*, it is the *polarization* of the plasma medium, and the associated redistribution of space charge, which prevents penetration by an external electric field. Not surprisingly, the length-scale associated with such shielding is the Debye length.



Let us consider the simplest possible example. Suppose that a quasi-neutral plasma is sufficiently close to thermal equilibrium that its particle densities are distributed according to the Maxwell-Boltzmann law,

$$n_s = n_0\, e^{-e_s\,\Phi/T}, \tag{11}$$

where $\Phi(\mathbf{r})$ is the electrostatic potential, and n_0 and T are constant. From $e_i = -e_e = e$, it is clear that quasi-neutrality requires the equilibrium potential to be a constant. Suppose that this equilibrium potential is perturbed, by an amount $\delta\Phi$, by a small, localized charge density $\delta\rho_{ext}$. The total perturbed charge density is written

$$\delta\rho = \delta\rho_{ext} + e\,(\delta n_i - \delta n_e) = \delta\rho_{ext} - 2\,e^2\,n_0\,\delta\Phi/T. \tag{12}$$

Thus, Poisson's equation yields

$$\nabla^2\delta\Phi = -\frac{\delta\rho}{\epsilon_0} = -\left(\frac{\delta\rho_{ext} - 2\,e^2\,n_0\,\delta\Phi/T}{\epsilon_0}\right), \tag{13}$$

which reduces to

$$\left(\nabla^2 - \frac{2}{\lambda_D^2}\right)\delta\Phi = -\frac{\delta\rho_{ext}}{\epsilon_0}. \tag{14}$$

If the perturbing charge density actually consists of a point charge q, located at the origin, so that $\delta\rho_{ext} = q\,\delta(\mathbf{r})$, then the solution to the above equation is written

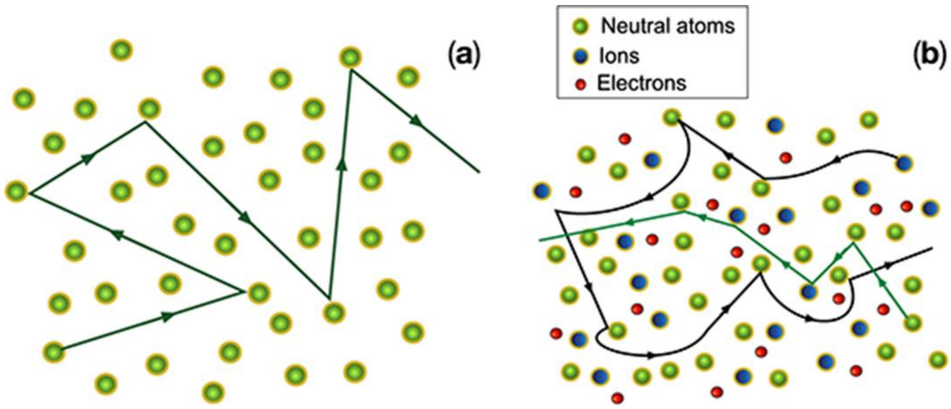
$$\delta\Phi(r) = \frac{q}{4\pi\epsilon_0\,r}\,e^{-\sqrt{2}\,r/\lambda_D}. \tag{15}$$

Clearly, the Coulomb potential of the perturbing point charge q is shielded on distance scales longer than the Debye length by a *shielding cloud* of approximate radius λ_D consisting of charge of the opposite sign.

2.2 Plasma Frequency

The *plasma frequency* is the most fundamental time-scale in plasma physics. Clearly, there is a different plasma frequency for each species. However, the relatively fast electron frequency is, by far, the most important, and references to ``the plasma frequency invariably mean the *electron* plasma frequency.

$$\omega_p^2 = \frac{n\,e^2}{\epsilon_0\,m}, \tag{5}$$



It is easily seen that ω_p corresponds to the typical electrostatic oscillation frequency of a given species in response to a small charge separation. For instance, consider a one-dimensional situation in which a slab consisting entirely of one charge species is displaced from its quasi-neutral position by an infinitesimal distance δx. The resulting charge density which develops on the leading face of the slab is $\sigma = e\,n\,\delta x$. An equal and opposite charge density develops on the opposite face. The x-directed electric field generated inside the slab is of magnitude $E_x = -\sigma/\epsilon_0 = -e\,n\,\delta x/\epsilon_0$. Thus, Newton's law applied to an individual particle inside the slab yields giving

$$m\,\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p^{\,2}\,\delta x, \tag{6}$$

$$\delta x = (\delta x)_0\,\cos(\omega_p\,t)$$

.

Note that plasma oscillations will only be observed if the plasma system is studied over time periods τ longer than the plasma period $\tau_p \equiv 1/\omega_p$, and if external actions change the system at a rate no faster than ω_p. In the opposite case, one is clearly studying something other than plasma physics (*e.g.*, nuclear reactions), and the system cannot not usefully be considered to be a plasma. Likewise, observations over length-scales L shorter than the distance $v_t\,\tau_p$ traveled by a typical plasma particle during a plasma period will also not detect plasma behaviour. In this case, particles will exit the system before completing a plasma oscillation. This distance, which is the spatial equivalent to τ_p, is called the *Debye length*, and takes the form

$$\lambda_D \equiv \sqrt{T/m}\;\omega_p^{-1}. \tag{7}$$

Note that

$$\lambda_D = \sqrt{\frac{\epsilon_0 T}{n e^2}} \tag{8}$$

is independent of mass, and therefore generally comparable for different species. Clearly, our idealized system can only usefully be considered to be a plasma provided that

$$\frac{\lambda_D}{L} \ll 1, \tag{9}$$

and

$$\frac{\tau_p}{\tau} \ll 1. \tag{10}$$

Here, τ and L represent the typical time-scale and length-scale of the process under investigation.

2.3 Plasma Parameter

Let us define the average distance between particles,

$$r_d \equiv n^{-1/3}, \tag{16}$$

and the distance of closest approach,

$$r_c \equiv \frac{e^2}{4\pi\epsilon_0 T}. \tag{17}$$

Recall that r_c is the distance at which the Coulomb energy

$$U(r, v) = \frac{1}{2} m v^2 - \frac{e^2}{4\pi\epsilon_0 r} \tag{18}$$

of one charged particle in the electrostatic field of another vanishes.

Thus, $U(r_c, v_t) = 0$.

The significance of the ratio r_d/r_c is readily understood. When this ratio is small, charged particles are dominated by one another's electrostatic influence more or less continuously, and their kinetic energies are small compared to the interaction potential energies. Such plasmas are termed *strongly coupled*. On the other hand, when the ratio is large, strong electrostatic interactions between individual particles are occasional and relatively rare events. A typical particle is electrostatically influenced by all of the other particles within its Debye sphere, but this interaction very rarely causes any sudden change in its motion. Such plasmas are termed *weakly coupled*. It is possible to describe a weakly coupled plasma using a standard Fokker-Planck equation (*i.e.*, the same type of equation as is conventionally used to describe a neutral gas). Understanding the strongly coupled limit is far more difficult, and will not be attempted in this course. Actually, strongly coupled plasma has more in common with a liquid than conventional weakly coupled plasma. Let us define the *plasma parameter*

$$\Lambda = 4\pi n \lambda_D^3. \qquad (19)$$

<u>This dimensionless parameter is obviously equal to the typical number of particles contained in a Debye sphere</u>. However, Eqs. (8), (16), (17), and (19) can be combined to give

$$\Lambda = \frac{\lambda_D}{r_c} = \frac{1}{\sqrt{4\pi}}\left(\frac{r_d}{r_c}\right)^{3/2} = \frac{4\pi\,\epsilon_0^{\,3/2}}{e^3}\,\frac{T^{3/2}}{n^{1/2}}. \tag{20}$$

It can be seen that the case $\Lambda \ll 1$, in which the Debye sphere is sparsely populated, corresponds to a strongly coupled plasma. Likewise, the case $\Lambda \gg 1$, in which the Debye sphere is densely populated, corresponds to **a weakly coupled plasma**. It can also be appreciated, from Eq. (20), that strongly coupled plasmas tend to be cold and dense, whereas weakly coupled plasmas are diffuse and hot. Examples of strongly coupled plasmas include solid-density laser ablation plasmas, the very ``cold'' (*i.e.*, with kinetic temperatures similar to the ionization energy) plasmas found in ``high pressure'' arc discharges, and the plasmas which constitute the atmospheres of collapsed objects such as white dwarfs and neutron stars.

On the other hand, the hot diffuse plasmas typically encountered in ionospheric physics, astrophysics, nuclear fusion, and space plasma physics are invariably weakly coupled. Table 1 lists the key parameters for some typical weakly coupled plasmas.

Table 1: *Key parameters for some typical weakly coupled plasmas.*

	$n(m^{-3})$	$T(eV)$	$\omega_p(sec^{-1})$	$\lambda_D(m)$	Λ
Interstellar	10^6	10^{-2}	6×10^4	0.7	4×10^6
Solar Chromosphere	10^{18}	2	6×10^{10}	5×10^{-6}	2×10^3
Solar Wind (1AU)	10^7	10	2×10^5	7	5×10^{10}
Ionosphere	10^{12}	0.1	6×10^7	2×10^{-3}	1×10^5
Arc discharge	10^{20}	1	6×10^{11}	7×10^{-7}	5×10^2
Tokamak	10^{20}	10^4	6×10^{11}	7×10^{-5}	4×10^8
Inertial Confinement	10^{28}	10^4	6×10^{15}	7×10^{-9}	5×10^4

In conclusion, characteristic *collective* plasma behaviour is only observed on time-scales longer than the plasma period, and on length-scales larger than the Debye length. The statistical character of this behaviour is controlled by the plasma parameter. Although ω_p, λ_D, and Λ are the three most fundamental plasma parameters.

2.4 Criteria for Plasmas

We have given two conditions that an ionized gas must satisfy to be called plasma. A third condition has to do with collisions. The weakly ionized gas in an airplane's jet exhaust, for example, does not qualify as plasma because the charged particles collide so frequently with neutral atoms that their motion is controlled by ordinary hydrodynamic forces rather than by electromagnetic forces. If ω is the frequency of typical plasma oscillations and τ is the mean time between collisions with neutral atoms, we require $\omega\tau > 1$ for the gas to behave like plasma rather than a neutral gas. The three conditions plasma must satisfy are therefore:

1. $\lambda_{D} < L$
2. $\Lambda \gg 1$
3. $\omega\tau > 1$

2.5 Collisions

Collisions between charged particles in plasma differ fundamentally from those between molecules in a neutral gas because of the long range of the Coulomb force. In fact, it is clear that *binary* collision processes can only be defined for weakly coupled plasmas. Note, however, that binary collisions in weakly coupled plasmas are still modified by collective effects--the many-particle process of Debye shielding enters in a crucial manner. Nevertheless, for large Λ we can speak of binary collisions, and therefore of a *collision frequency*, denoted by $\nu_{ss'}$. Here, $\nu_{ss'}$ measures the rate at which particles of species s are scattered by those of species s'. When specifying only a single subscript, one is generally referring to the *total* collision rate for that species, including impacts with all other species. Very roughly,

$$\nu_s \simeq \sum_{s'} \nu_{ss'}. \tag{21}$$

The species designations are generally important. For instance, the relatively small electron mass implies that, for unit ionic charge and comparable species temperatures,

$$\nu_e \sim \left(\frac{m_i}{m_e}\right)^{1/2} \nu_i. \tag{22}$$

Note that the collision frequency ν measures the frequency with which a particle trajectory undergoes a *major* angular change due to Coulomb interactions with other particles. Coulomb collisions are, in fact, predominately small angle scattering events, so the collision frequency is *not* the inverse of the typical time between collisions. Instead, it is the inverse of the typical time needed for enough collisions to occur that the particle trajectory is deviated through 90°. For this reason, the collision frequency is sometimes termed the ``90° scattering rate." It is conventional to define the *mean-free-path*,

$$\lambda_{mfp} \equiv v_t/\nu. \tag{23}$$

Clearly, the mean-free-path measures the typical distance a particle travels between ``collisions'' (*i.e.*, 90° scattering events). A collision-dominated, or *collisional*, plasma is simply one in which

$$\lambda_{mfp} \ll L, \tag{24}$$

where L is the observation length-scale. The opposite limit of large mean-free-path is said to correspond to a *collisionless* plasma. Collisions greatly simplify plasma behaviour by driving the system towards statistical equilibrium, characterized by Maxwell-Boltzmann distribution functions. Furthermore, short mean-free-paths generally ensure that plasma transport is *local* (*i.e.*, diffusive) in nature, which is a considerable simplification. The typical magnitude of the collision frequency is

$$\nu \sim \frac{\ln \Lambda}{\Lambda}\, \omega_p. \tag{25}$$

Note that $\nu \ll \omega_p$ in weakly coupled plasma. It follows that collisions do not seriously interfere with plasma oscillations in such systems. On the other hand, Eq. (25) implies that $\nu \gg \omega_p$ in a strongly coupled plasma, suggesting that collisions effectively prevent plasma oscillations in such systems. This accord well with our basic picture of strongly coupled plasma as a system dominated by Coulomb interactions which does not exhibit conventional plasma dynamics. It follows from Eqs. (5) and (20) that

$$\nu \sim \frac{e^4 \ln \Lambda}{4\pi\epsilon_0^2\, m^{1/2}} \frac{n}{T^{3/2}}. \tag{26}$$

Thus, diffuse, high temperature plasmas tend to be collisionless, whereas dense, low temperature plasmas are more likely to be collisional.

Note that whilst collisions are crucial to the confinement and dynamics (*e.g.*, sound waves) of neutral gases, they play a far less important role in plasmas. In fact, in many types of plasma the magnetic field effectively plays the role that collisions play in a neutral gas. In such plasmas, charged particles are constrained from moving perpendicular to the field by their small Larmor orbits, rather than by collisions. Confinement along the field-lines is more difficult to achieve, unless the field-lines form closed loops (or closed surfaces). Thus, it makes sense to talk about a ``collisionless plasma," whereas it makes little sense to talk about a ``collisionless neutral gas." Note that many plasmas are collisionless to a very good approximation, especially those encountered in astrophysics and

space plasma physics contexts.

2.6 Magnetized Plasmas

A *magnetized* plasma is one in which the ambient magnetic field $\mathbf{B}$ is strong enough to significantly alter particle trajectories. In particular, magnetized plasmas are *anisotropic*, responding differently to forces which are parallel and perpendicular to the direction of $\mathbf{B}$. Note that magnetized plasma moving with mean velocity $\mathbf{V}$ contains an electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ which is *not affected* by Debye shielding. Of course, in the rest frame of the plasma the electric field is essentially zero.

As is well-known, charged particles respond to the Lorentz force,

$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}, \tag{27}$$

by freely streaming in the direction of $\mathbf{B}$, whilst executing circular Larmor orbits, or *gyro-orbits*, in the plane perpendicular to $\mathbf{B}$. As the field-strength increases, the resulting helical orbits become more tightly wound, effectively tying particles to magnetic field-lines. The typical Larmor radius, or *gyroradius*, of a charged particle gyrating in a magnetic field is given by

$$\rho \equiv \frac{v_t}{\Omega}, \tag{28}$$

where

$$\Omega = eB/m \tag{29}$$

is the cyclotron frequency, or *gyrofrequency*, associated with the gyration. As usual, there is a distinct gyroradius for each species. When species temperatures are comparable, the electron gyroradius is distinctly smaller than the ion gyroradius:

$$\rho_e \sim \left(\frac{m_e}{m_i}\right)^{1/2} \rho_i. \tag{30}$$

A plasma system, or process, is said to be *magnetized* if it's characteristic length-scale L is large compared to the gyroradius. In the opposite limit, $\rho \gg L$, charged particles have essentially straight-line trajectories. Thus, the ability of the magnetic field to significantly affect particle trajectories is measured by the *magnetization parameter*

$$\delta \equiv \frac{\rho}{L}. \qquad (31)$$

There are some cases of interest in which the electrons are magnetized, but the ions are not. However, a ``magnetized" plasma conventionally refers to one in which both species are magnetized. This state is generally achieved when

$$\delta_i \equiv \frac{\rho_i}{L} \ll 1.$$

3.1 Plasma Generation Techniques

DC Glow Discharge: This belongs to non-thermal plasma, in which Direct current (DC) electric source is connecting between cathode and anode plate and the application of plasma gas is performed among the plates for plasma generation.

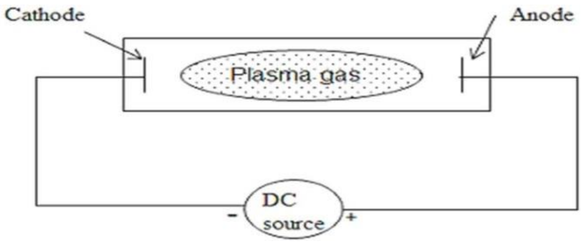


Figure.1 System for DC glow discharge

The application of DC electrical field across the cathode and anode plate causes the acceleration of electrons in the front end of the cathode, which increases the inelastic collision between atoms and electrons and leading towards the ionization and excitation. Ions and new electrons created by the ionization collision are strongly accelerated by the electric field toward the cathode that discharges the new electrons by ion- induced through the secondary electron emission. The increase ionization collisions increase the concentration of new electrons and ions at the cathode build the discharge glow of self-sustaining plasma. The emitted electrons from the electrodes usually unable to sustain the discharge when there will be no potential difference between the electrodes, while the injection of constant potential difference increases the DC discharge because of the large flowing of current. This can be extensively utilized for material processing, as a light source, etching, Ion-deposition and for physical mechanism of surface modification.

i- Radio Frequency Discharge:

It produces the plasma either by inductively or capacitively coupling energy at frequency range lies under the radio spectrum (1KHz to 103MHz) and has AC power supply. Based on the coupling mechanism, there exist two kinds of RF plasma discharge, i.e., the Capacitively Coupled Discharge (CCD) and Inductively Coupled Discharge (ICD). Within capacitively coupled discharge system, the AC voltage source is provided to power electrodes through a capacitor, while the other electrode is solidly grounded. The capacitor rapidly charged at the positive half of the voltage source, which causes the voltage drop over the plasma. The charging up of the capacitor by the ion current and dropping of plasma voltage likely occurs in the negative half cycle but the voltage is much prevalent of the lower ion mobility. It preferably utilizes as a lower temperature processing medium of plasma for material processing in aerospace and microelectronics fields.

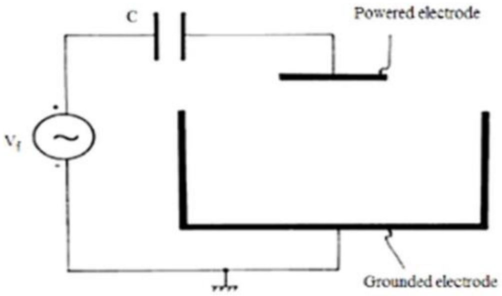


Figure.2Capacitively coupled discharge system

The inductive coupled discharge contains the configuration of a cylindrical helical coil, in which the electromagnetic induction provides the corresponding electric current. The passing of RF current through the coil develop the time-varying magnetic flux that largely induces the RF sinusoidal electrical field that sustains the plasma discharge and accelerate the free electrons.

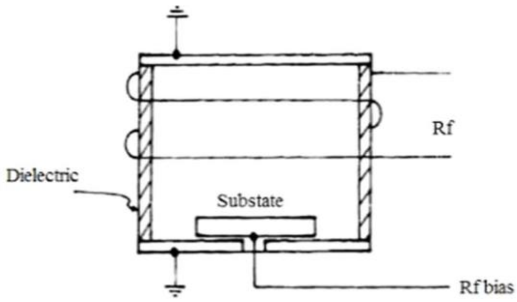


Figure.3 Inductively coupled discharge system

Transformer coupling usually aid for inducing the electromagnetic field between the induction coil and plasma at a frequency range of 1 to 100 MHz It is much efficient for generating the oscillation and electron acceleration in the curved orbits that cause a significant decrease of electron losses with the walls. It is preferable to use in deposition and etching for processing of semiconductor wafers, for modifying the surface surfaces of diamond films and fabrication purposes.

ii. Hydrogen Production from alcohols

Non-thermal Plasma has more applications in the industry than thermal Plasma. Methanol has high H to C ratio. Methanol can be made from methane, which is abundant. Conversion of methanol to hydrogen can be made done by Dielectric Barrier Discharge (DBD) Plasma, corona discharge Plasma, surface-wave discharge Plasma, Microwave Plasma, glow discharge Plasma, pulse charge Plasma, etc. DBD is also known as silent Plasma. It is generating by using the two electrodes, which have a barrier between them made up of dielectric of few millimeters in thickness. Three different variants of the setup used for making DBD Plasma are shown in Fig. 4.

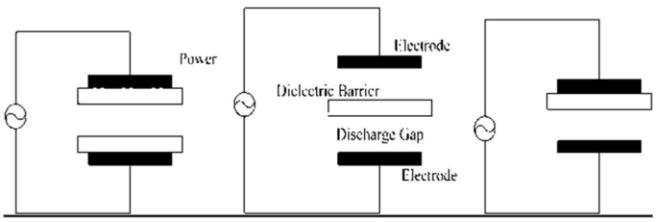


Figure.4 Three basic configurations

The useful product from the decomposition of methanol is hydrogen and byproducts are CO and CO_2. The highest yield of hydrogen achievable by this process to date is about 28%

Glow discharge

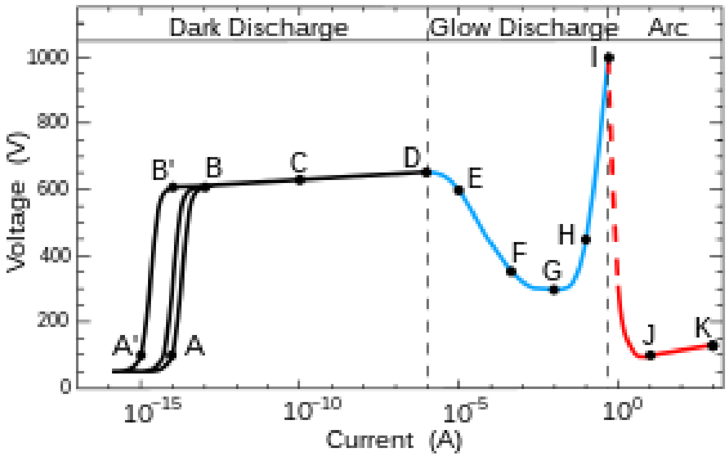
A glow discharge is a plasma formed by the passage of electric current through a gas. It is often created by applying a voltage between two electrodes in a glass tube containing a low-pressure gas. When the voltage exceeds a value called the striking voltage, the gas ionization becomes self-sustaining, and the tube glows with a colored light. The color depends on the gas used. Glow discharges are used as a source of light in devices such as neon lights, fluorescent lamps, and plasma-screen televisions. Analyzing the light produced with spectroscopy can reveal information about the atomic interactions in the gas, so glow discharges are used in plasma physics and analytical chemistry. They are also used in the surface treatment technique called sputtering.

Electrical conduction in gas

Conduction in a gas requires charge carriers, which can be either electrons or ions. Charge carriers come from ionizing some of the gas molecules. In terms of current flow, glow discharge falls between dark discharge and arc discharge.

In a dark discharge, the gas is ionized (the carriers are generated) by a radiation source such as ultraviolet light or Cosmic rays. At higher voltages across the anode and cathode, the freed carriers can gain enough energy so that additional carriers are freed during collisions; the process is a Townsend avalanche or multiplication.

In a glow discharge, the carrier generation process reaches a point where the average electron leaving the cathode allows another electron to leave the cathode. For example, the average electron may cause dozens of ionizing collisions via the Townsend avalanche; the resulting positive ions head toward the cathode, and a fraction of those that cause collisions with the cathode will dislodge an electron by secondary emission. In an arc discharge, electrons leave the cathode by thermionic emission and field emission, and the gas is ionized by thermal means. Below the breakdown voltage there is little to no glow and the electric field is uniform. When the electric field increases enough to cause ionization, the Townsend discharge starts. When a glow discharge develops, the electric field is considerably modified by the presence of positive ions; the field is concentrated near the cathode. The glow discharge starts as a normal glow. As the current is increased, more of the cathode surface is involved in the glow. When the current is increased above the level where the entire cathode surface is involved, the discharge is known as an abnormal glow. If the current is increased still further, other factors come into play and an arc discharge begins.



Voltage-current characteristics of electrical discharge in neon at 1 torr, with two planar electrodes separated by 50 cm.

A: random pulses by cosmic radiation

B: saturation current

C: avalanche Townsend discharge

D: self-sustained Townsend discharge

E: unstable region: corona discharge

F: sub-normal glow discharge

G: normal glow discharge

H: abnormal glow discharge

I: unstable region: glow-arc transition

J: electric arc

K: electric arc

A-D region: dark discharge; ionisation occurs, current below 10 microamps.

F-H region: glow discharge; the plasma emits a faint glow.

I-K region: arc discharge; large amounts of radiation produced.

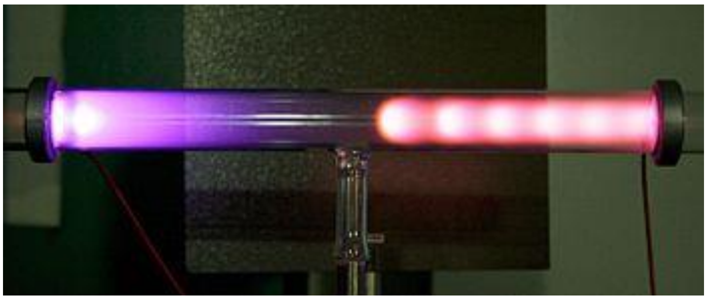
Mechanism

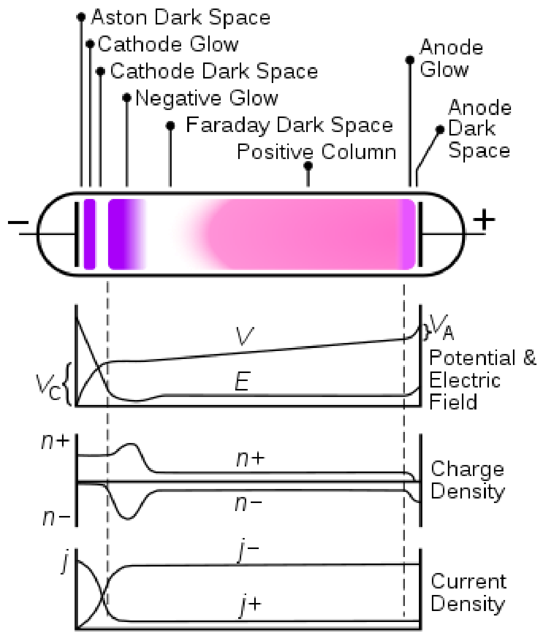
The simplest type of glow discharge is a direct-current glow discharge. In its simplest form, it consists of two electrodes in a cell held at low pressure (0.1–10 torr; about 1/10000th to 1/100th of atmospheric pressure). A low pressure is used to increase the mean free path; for a fixed electric field, a longer mean free path allows a charged particle to gain more energy before colliding with another particle. The cell is typically filled with neon, but other gases can also be used. An electric potential of several hundred volts is applied between the two electrodes. A small fraction of the population of atoms within the cell is initially ionized through random processes, such as thermal collisions between atoms or by gamma rays. The positive ions are driven towards the cathode by the electric potential, and the electrons are driven towards the anode by the same potential. The initial population of ions and electrons collides with other atoms, exciting or ionizing them. As long as the potential is maintained, a population of ions and electrons remains.

Secondary emission

Some of the ions' kinetic energy is transferred to the cathode. This happens partially through the ions striking the cathode directly. The primary mechanism, however, is less direct. Ions strike the more numerous neutral gas atoms, transferring a portion of their energy to them. These neutral atoms then strike the cathode. Whichever species (ions or atoms) strike the cathode, collisions within the cathode redistribute this energy resulting in electrons ejected from the cathode. This process is known as secondary electron emission. Once free of the cathode, the electric field accelerates electrons into the bulk of the glow discharge. Atoms can then be excited by collisions with ions, electrons, or other atoms that have been previously excited by collisions.

Regions





A glow discharge illustrating the different regions comprising it and a diagram giving their names.

The illustrations to the right shows the main regions that may be present in a glow discharge. Regions described as "glows" emit significant light; regions labeled as "dark spaces" do not. As the discharge becomes more extended (i.e., stretched horizontally in the geometry of the illustrations), the positive column may become striated. That is, alternating dark and bright regions may form. Compressing the discharge horizontally will result in fewer regions. The positive column will be compressed while the negative glow will remain the same size, and, with small enough gaps, the positive column will disappear altogether. In an analytical glow discharge, the discharge is primarily a negative glow with dark region above and below it.

Cathode layer

The cathode layer begins with the Aston dark space, and ends with the negative glow region. The cathode layer shortens with increased gas pressure. The cathode layer has a positive space charge and a strong electric field.

Aston dark space

Electrons leave the cathode with an energy of about 1 eV, which is not enough to ionize or excite atoms, leaving a thin dark layer next to the cathode.

Cathode glow

Electrons from the cathode eventually attain enough energy to excite atoms. These excited atoms quickly fall back to the ground state, emitting light at a wavelength corresponding to the difference between the energy bands of the atoms. This glow is seen very near the cathode.

Cathode dark space

As electrons from the cathode gain more energy, they tend to ionize, rather than excite atoms. Excited atoms quickly fall back to ground level emitting light, however, when atoms are ionized, the opposite charges are separated, and do not immediately recombine. This results in more ions and electrons, but no light.[3] This region is sometimes called Crookes dark space, and sometimes referred to as the cathode fall, because the largest voltage drop in the tube occurs in this region.

Negative glow

The ionization in the cathode dark space results in a high electron density, but slower electrons, making it easier for the electrons to recombine with positive ions, leading to intense light, through a process called bremsstrahlung radiation.

Faraday dark space

As the electrons keep losing energy, less light is emitted, resulting in another dark space.

Anode layer

The anode layer begins with the positive column, and ends at the anode. The anode layer has a negative space charge and a moderate electric field.

Positive column

With fewer ions, the electric field increases, resulting in electrons with energy of about 2 eV, which is enough to excite atoms and produce light. With longer glow discharge tubes, the longer space is occupied by a longer positive column, while the cathode layer remains the same. For example, with a neon sign, the positive column occupies almost the entire length of the tube.

Anode glow

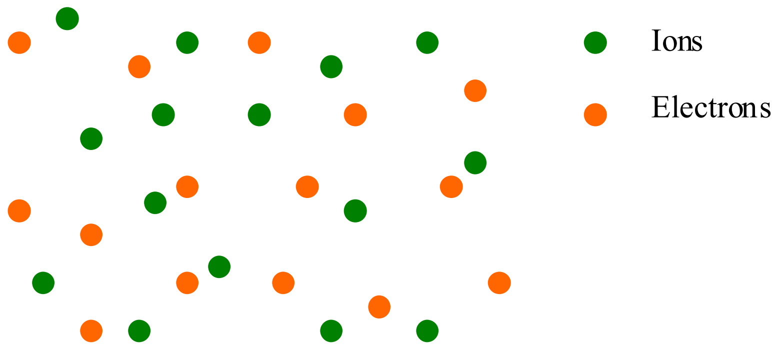
An electric field increase results in the anode glow.

Anode dark space

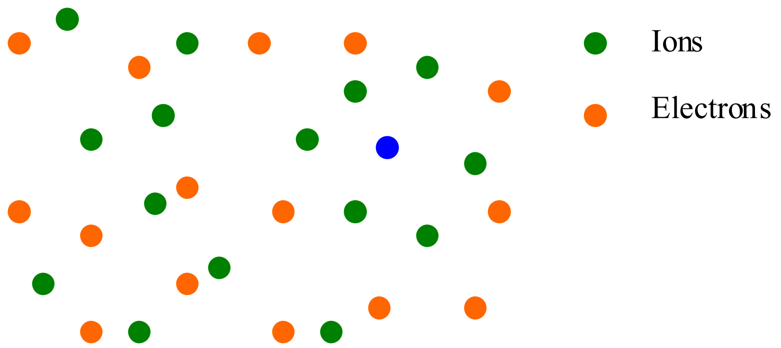
Fewer electrons results in another dark space.

Charged particle motion

Plasmas, by their very nature, exhibit collective behavior. Let us assume that we have a single electron in a plasma which we can move at will. If that electron is not in the system, the rest of the electrons and the ions will spread out in an approximately even distribution across the system. (Note that this is even distribution has a lot of qualifications. For example walls greatly disturb the charges… We will get to this more later.) Under this situation the distribution of charges might look like:



Now let us add our electron (noting that we could as easily have done this with an ion):



Because our electron tends to push the other electrons away and draw the ions toward it we find that we have rearranged our distributions. If our test charge now has some motion to it, we find that all of the charged particles in a local area respond to this motion. This is a collective behavior that is a requirement for our system to be in the plasma state. In general it is the collective behavior that is most important to understanding how a plasma operates. Unfortunately it also is fairly intensive mathematically. On the other hand, we can develop an understanding of the plasma if we look at single particle motion in the plasma. (We just have to remember that the rest of the charged particles move in response to the motion that we are modeling and hence we change the E and B fields on our test charge.)

Lorentz force

The equation of motion for a single particle of charge q and mass m is given by the Lorentz force law: $m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$.

While this equation can be quite complex, for complex fields, it is often easiest to look at the cases when the external fields are simple.

Case 1: $\mathbf{E} = E_z\hat{\mathbf{z}}; \quad \mathbf{B} = 0$

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$$

$$= \frac{q}{m}E_z\hat{\mathbf{z}}$$

Integrating gives

$$x = x_0 + v_{x0}t$$
$$y = y_0 + v_{y0}t$$
$$z = z_0 + v_{z0}t + \frac{q}{2m}E_z t^2$$

$$\left\{\begin{array}{ll} \text{Letting} & \mathbf{E} = \mathbf{E}_0; \quad \mathbf{B} = 0 \\ \text{Gives} & \mathbf{r} = \mathbf{r}_0 + \mathbf{v}_0 + \dfrac{q}{2m}\mathbf{E}_0 t^2 \end{array}\right\}$$

This is quite simple and not terribly informative.

This would imply that the charged particle accelerates to infinite velocities. In real systems the electric field does not extend to infinity and collisions tend to slow the particle down. (Run away charged particles do occur – eventually running into walls – resulting in the production of Deep UV and x-ray production in some plasma systems.)

Cases 2: $\mathbf{E} = 0; \quad \mathbf{B} = B_0\hat{\mathbf{z}}$

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$$
$$= \frac{q}{m}\mathbf{v} \wedge B_0\hat{\mathbf{z}}$$

Thus we find

$$\frac{dv_x}{dt} = \frac{q}{m}v_y B_0$$
$$\frac{dv_y}{dt} = -\frac{q}{m}v_x B_0$$
$$\frac{dv_z}{dt} = 0$$

To solve this set of equations, we must separate the components of the velocity. This is simple to do by differentiating the equations again and substituting to give.

$$\frac{d^2v_x}{dt^2} = \frac{q}{m}\frac{dv_y}{dt}B_0 = -\left(\frac{q}{m}B_0\right)^2 v_x$$
$$\frac{d^2v_y}{dt^2} = -\frac{q}{m}\frac{dv_x}{dt}B_0 = -\left(\frac{q}{m}B_0\right)^2 v_y$$
$$\frac{d^2v_z}{dt^2} = 0$$

These second order equations are of course are easily solved as

$$v_x = v_{x0}e^{\pm i\omega_c t}$$
$$v_y = v_{y0}e^{\pm i\omega_c t} \quad \text{where} \quad \omega_c = \frac{q}{m}B_0$$
$$v_z = v_{z0}$$

Now taking into account the original coupled first order equations we find

$$v_x = v_{\perp 0}\cos(\omega_c t + \varphi)$$
$$v_y = -v_{\perp 0}\sin(\omega_c t + \varphi)$$
$$v_z = v_{z0}$$

Integrating a second time we find,

$$x = \frac{v_{\perp 0}}{\omega_c}\sin(\omega_c t + \varphi) + x_0 - \frac{v_{\perp 0}}{\omega_c}\sin(\varphi)$$
$$y = \frac{v_{\perp 0}}{\omega_c}\cos(\omega_c t + \varphi) + y_0 - \frac{v_{\perp 0}}{\omega_c}\cos(\varphi)$$
$$z = v_{z0}t + z_0$$
$$r_c = \frac{v_{\perp 0}}{\omega_c}$$

It is easy to see that $r_c = \frac{v_{\perp 0}}{\omega_c}$ is the radius of a circular orbit around the magnetic field line; it is known as the Larmor radius or the cyclotron radius. Further we note that the positively charged particles orbit in a left-hand orbit while the negatively charged particles orbit in a right-hand orbit.

Example

Of particular interest is the magnetic field required to give an electron a gyro-frequency of 2.45 GHz. This is of interest because it is required to understand Electron Cyclotron Resonance, ECR, plasma sources. (Given time at the end of the semester, we will discuss these sources in detail.)

$$\begin{aligned} f_c &= \frac{\omega_c}{2\pi} \\ &= \frac{q}{2\pi m} B_0 \\ &= 2.8E6 \;\; B_0 \;\; (Hz / Gauss) \\ &\Downarrow \\ B_0 &\approx 875\, G \end{aligned}$$

Case 3: $\mathbf{E} = E_z \hat{\mathbf{z}}; \quad \mathbf{B} = B_0 \hat{\mathbf{z}}$

$$\begin{aligned} \frac{d\mathbf{v}}{dt} &= \frac{q}{m}(\mathbf{E} + \mathbf{v} \wedge \mathbf{B}) \\ &= \frac{q}{m}\left(E_z \hat{\mathbf{z}} + \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ v_x & v_y & v_z \\ 0 & 0 & B_0 \end{vmatrix} \right) \end{aligned}$$

or

$$\begin{aligned} \frac{dv_x}{dt} &= \frac{q}{m} v_y B_0 \\ \frac{dv_y}{dt} &= -\frac{q}{m} v_x B_0 \\ \frac{dv_z}{dt} &= \frac{q}{m} E_z \end{aligned}$$

This is easy to solve as we have already done this as parts.

$$x = r_c \sin(\omega_c t + \varphi) + x_0 - r_c \sin(\varphi)$$
$$y = r_c \cos(\omega_c t + \varphi) + y_0 - r_c \cos(\varphi)$$
$$z = z_0 + v_{z0} t + \frac{q}{2m} E_z t^2$$
$$r_c = \frac{v_{\perp 0}}{\omega_c}$$

Case 4: $\mathbf{E} = E_x \hat{\mathbf{x}}$; $\mathbf{B} = B_0 \hat{\mathbf{z}}$: Note that $\mathbf{E} = E_y \hat{\mathbf{y}}$ would also work here

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$$
$$= \frac{q}{m}\left(E_x \hat{\mathbf{x}} + \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ v_x & v_y & v_z \\ 0 & 0 & B_0 \end{vmatrix} \right) \quad or$$

$$\frac{dv_x}{dt} = \frac{q}{m} E_x + \omega_c v_y \quad \Rightarrow \quad ?$$
$$\frac{dv_y}{dt} = -\omega_c v_x \quad \Rightarrow \quad ?$$
$$\frac{dv_z}{dt} = 0 \quad \Rightarrow \quad v_z = v_{z0}; \; z = v_z t + z_0$$

The third equation is easy to solve while the first two are more difficult.

Differentiating gives

$$\frac{d^2v_x}{dt^2} = -\omega_c^2 v_x$$
$$\Downarrow$$
$$v_x = v_{x0} e^{\pm i\omega_c t}$$

$$\frac{d^2v_y}{dt^2} = -\omega_c\left(\frac{q}{m}E_x + \omega_c v_y\right)$$
$$= -\omega_c\left(\frac{qB_0}{m}\frac{E_x}{B_0} + \omega_c v_y\right)$$
$$= -\omega_c^2\left(\frac{E_x}{B_0} + v_y\right) \text{ but } \frac{d^2v_y}{dt^2} = \frac{d^2}{dt^2}\left(v_y + \frac{E_x}{B_0}\right) \text{ so}$$
$$v_y + \frac{E_x}{B_0} = v_{y0} e^{\pm i\omega_c t}$$
$$v_y = v_{y0} e^{\pm i\omega_c t} - \frac{E_x}{B_0}$$

Plugging these into our initial equations gives

$$\frac{dv_x}{dt} = \frac{q}{m}E_x + \omega_c\left(v_{y0}e^{\pm i\omega_c t} - \frac{E_x}{B_0}\right)$$
$$= \omega_c v_{y0} e^{\pm i\omega_c t}$$
$$= \pm i\omega_c v_{x0} e^{\pm i\omega_c t}$$
$$\Downarrow$$
$$v_{y0} = \pm i v_{x0}$$

Let $v_\perp = \mp i v_{y0} = v_{x0}$ giving

$$v_x = v_\perp e^{\pm i\omega_c t} \Rightarrow v_\perp \cos(\omega_c t + \phi)$$
$$v_y = \mp i v_\perp e^{\pm i\omega_c t} - \frac{E_x}{B_0} \Rightarrow v_\perp \sin(\omega_c t + \phi) - \frac{E_x}{B_0}$$
$$v_z = v_{z0};\ z = v_z t + z_0$$

This means that the particle travels along the as it would with just the magnetic field but it also have a drift in the $\mathbf{E} \wedge \mathbf{B}$ direction. We can calculate this in general. First the average force is

$$\langle \mathbf{F} \rangle = q(\mathbf{E} + \langle \mathbf{v} \rangle \wedge \mathbf{B}) = 0$$

Therefore

$$\langle \mathbf{F} \rangle \wedge \mathbf{B} = q(\mathbf{E} \wedge \mathbf{B} + (\langle \mathbf{v} \rangle \wedge \mathbf{B}) \wedge \mathbf{B}) = 0$$

$$\Downarrow$$

$$\begin{aligned} \mathbf{E} \wedge \mathbf{B} &= -(\langle \mathbf{v} \rangle \wedge \mathbf{B}) \wedge \mathbf{B} \\ &= \mathbf{B} \wedge (\langle \mathbf{v} \rangle \wedge \mathbf{B}) \\ &= \langle \mathbf{v} \rangle (\mathbf{B} \bullet \mathbf{B}) - \mathbf{B}(\langle \mathbf{v} \rangle \bullet \mathbf{B}) \end{aligned}$$

Now if there is no drift along **B** then we get

$$\langle \mathbf{v} \rangle = \frac{\mathbf{E} \wedge \mathbf{B}}{B^2}$$

What we have described above is true in general. Assuming that we have any constant force that is a right angle to the magnetic field.

$$\mathbf{F}_{total} \wedge \mathbf{B} = 0 = \mathbf{F}_{\perp} \wedge \mathbf{B} + q(\mathbf{v} \wedge \mathbf{B}) \wedge \mathbf{B}$$

$$\Downarrow$$

$$\mathbf{v}_{drift} = \frac{\mathbf{F}_{\perp} \wedge \mathbf{B}}{qB^2}$$

Case 5: $\mathbf{E} = 0; \quad \mathbf{B} = \mathbf{B}_0 + (\mathbf{r} \bullet \nabla)\mathbf{B} + \ldots$: Non-uniform magnetic field

Here we look at a magnetic field that is non-uniform in space. The Taylor series expansion of such a field will be of the form

$$\mathbf{B} = \mathbf{B}_0 + (\mathbf{r} \bullet \nabla)\mathbf{B} + \ldots$$

This should be straight forward from

$$B_z(y) = B_{z0} + y\partial_y B_z + \ldots$$

Now from Lorentz's Force Law we have

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \wedge \mathbf{B}) = q(\mathbf{v} \wedge \mathbf{B})$$

or in the y-direction

$$m\frac{dv_y}{dt} = -qv_x B_z$$
$$= -qv_x\left(B_{z0} + y\partial_y B_z + ...\right)$$

(We can do the same thing in the x-direction.)

The force averaged over one gyration is

$$m\left\langle\frac{dv_y}{dt}\right\rangle = -q\left(\langle v_x\rangle B_{z0} + \langle yv_x\rangle\partial_y B_z + ...\right)$$

The first term is clearly zero. The second term is not as

$$\langle yv_x\rangle = \left\langle\left(r_c\cos(\omega_c t + \varphi) + y_0 - r_c\cos(\varphi)\right)\left(v_{\perp 0}\cos(\omega_c t + \varphi)\right)\right\rangle$$
$$= r_c v_{\perp 0}\left\langle\cos^2(\omega_c t + \varphi)\right\rangle \text{ - all of the other terms are zero}$$
$$= \frac{1}{2} r_c v_{\perp 0}$$

We can now plug this into our average force equation to get

$$m\left\langle\frac{dv_y}{dt}\right\rangle = -q\frac{1}{2} r_c v_{\perp 0}\partial_y B_z \text{ – or in general}$$
$$= -q\frac{1}{2} r_c v_{\perp 0}\nabla B_z$$
$$= \frac{1}{2} m v_{\perp 0}^2 \frac{1}{B}\nabla B_z$$

In the x-direction this becomes

$$m\left\langle \frac{dv_x}{dt} \right\rangle = -q\left(\langle v_y \rangle B_{z0} + \langle y v_y \rangle \partial_y B_z + \ldots\right)$$

but

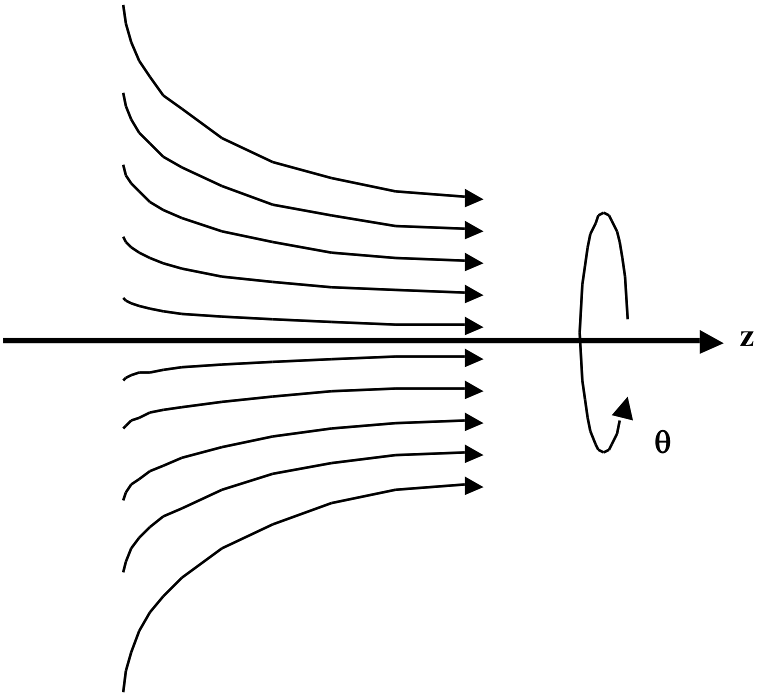
$$\langle y v_y \rangle = \left\langle \left(r_c \cos(\omega_c t + \varphi) + y_0 - r_c \cos(\varphi)\right)\left(v_{\perp 0} \sin(\omega_c t + \varphi)\right) \right\rangle$$
$$= r_c v_{\perp 0} \langle \cos(\omega_c t + \varphi) \sin(\omega_c t + \varphi) \rangle$$
$$= 0$$

Thus, we have from above a drift velocity

$$\mathbf{v}_{drift} = \frac{\mathbf{F}_\perp \wedge \mathbf{B}}{qB^2}$$
$$= \frac{1}{2} r_c v_{\perp 0} \frac{\mathbf{B} \wedge \nabla B_z}{B^2}$$
$$= \frac{1}{2} m v_{\perp 0}^2 \frac{1}{B} \frac{\mathbf{B} \wedge \nabla B_z}{B^2}$$

This leads into a topic known as magnetic mirrors. Magnetic mirrors are naturally occurring phenomena that happen at the magnetic poles of planets and stars. In laboratory-based plasmas magnetic mirror are used in some process systems to confine the plasma. (They were also used – quite unsuccessfully - as a confinement mechanism for fusion plasmas.)

In a mirror the gradient of the magnetic field is parallel to the direction of the field lines. This sort of arrangement is known as a cusp field and looks like the figure below. (This is the geometry one finds with permanent magnets.)



From Maxwell's Equations we have

$$\nabla \bullet \mathbf{B} = 0$$

$\Downarrow$ - in cylindrical coordinates

$$\mathrm{r}^{-1}\partial_r(rB_r) + \partial_z(B_z) = 0 \quad \text{- or}$$

$$\mathrm{r}^{-1}\partial_r(rB_r) = -\partial_z(B_z)$$

Integrating over r and assuming $\partial_z(B_z)$ is not a function r gives

$$\int \partial_r(rB_r)dr = -\int r\partial_z(B_z)dr$$

$$rB_r \approx -\frac{r^2}{2}\partial_z(B_z)\Big|_{r=0}$$

$$B_r \approx -\frac{r}{2}\partial_z(B_z)\Big|_{r=0}$$

Now from Lorentz,

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$$
$$\Downarrow$$
$$F_r = q\left(v_\theta B_z - v_z \overbrace{B_\theta}^{=0} \right) = q v_\theta B_z$$
$$F_\theta = q(v_z B_r - v_r B_z)$$
$$F_z = q\left(v_r \overbrace{B_\theta}^{=0} - v_\theta B_r \right) = -q v_\theta B_r = q v_\theta \frac{r}{2} \partial_z (B_z)\Big|_{r=0}$$

Now

$$v_\theta = \sqrt{v_x^2 + v_y^2} \quad \text{has to do with the direction of } \theta.$$
$$= \mp v_\perp$$

and

$$r = r_c = \frac{v_\perp}{\omega_c} \quad \text{where} \quad \omega_c = \frac{q}{m} B_0$$

Thus

$$F_z = \mp q v_\perp \frac{r_c}{2} \partial_z (B_z)$$
$$= \mp q \frac{v_\perp^2}{2\omega_c} \partial_z (B_z)$$
$$= -\tfrac{1}{2} m v_\perp^2 \frac{1}{B} \partial_z (B_z)$$
$$= -\mu \partial_z (B_z) \quad \text{where} \quad \mu = \tfrac{1}{2} m v_\perp^2 \frac{1}{B}$$

μ is the magnetic moment of a particle gyrating around a point. This can be easily seen from

$\mu = IA$ - where I and A are the current and area

$$= \left(\frac{q\omega_c}{2\pi}\right)\left(\pi r_c^2\right)$$

$$= \frac{qv_\perp^2}{2\omega_c}$$

$$= \frac{\frac{1}{2}mv_\perp^2}{B}$$

What does this mean?

As a particle moves into a region of increasing B, the Larmor radius shrinks but the magnetic moment remains constant. (This is shown in a number of books, including Chen.) Since the B field strength is increasing the particles tangential velocity must increase to keep μ constant. The total energy of the particle must also remain constant and thus the particle velocity parallel to the magnetic field must decrease. This causes the particle to bounce off of the 'magnetic mirror'. (There are still ways for some of the particles to 'leak' through the mirror. This is one of the major reasons that magnetic mirrors did not work in the fusion field.)

Additional drift motions

There are a number of additional drift motions that occur for single particles. We unfortunately do not have time to cover these drifts. The other drifts include:

Curved **B**: Curvature drift

Non-uniform **E**

Curved Vacuum fields

Polarization Drift.

Most of these are covered in the main text or in Chen.

3.2 Principles of magnetic confinement

Magnetic confinement of plasmas is the most highly developed approach to controlled fusion. A large part of the problem of fusion has been the attainment of magnetic field configurations that effectively confine the plasma. A successful configuration must meet three criteria:

(1) The plasma must be in a time-independent equilibrium state.

(2) The equilibrium must be macroscopically stable.

(3) The leakage of plasma energy to the bounding wall must be small.

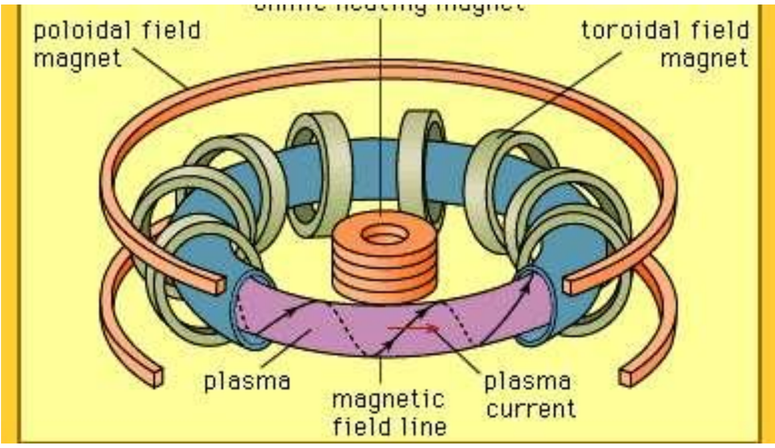
Charged particles tend to spiral about a magnetic line of force. It is necessary that these particle trajectories do not intersect the bounding wall. Simultaneously, the thermal energy of all the particles exerts an expansive pressure force on the plasma. For the plasma to be in equilibrium, the magnetic force acting on the electric current within the plasma must balance the pressure force at every point in the plasma. This equilibrium must be stable, which is to say that the plasma will return to its original state following any small perturbation, such as continual random thermal "noise" fluctuations. In contrast, unstable plasma would likely depart from its equilibrium state and rapidly (perhaps in less than one-thousandth of a second) escape the confining magnetic field following any small perturbation.

Plasma in stable equilibrium can be maintained indefinitely if the leakage of energy from the plasma is balanced by energy input. If the plasma energy loss is too large, then ignition cannot be achieved. An unavoidable diffusion of energy across the magnetic field lines will occur from the collisions between the particles. The net effect is to transport energy from the hot core to the wall. In theory, this transport process, known as classical diffusion, is not strong in hot fusion plasmas and can be compensated by heat from the alpha particle fusion products. In experiments, however, energy is lost from the plasma at 10 to 100 times that expected from classical diffusion theory. Solution of the anomalous transport problem involves research into fundamental topics in plasma physics, such as plasma turbulence. Many different types of magnetic configurations for plasma confinement have been devised and tested over the years. These may be grouped into two classes: **closed, toroidal configurations** and **open, linear configurations.**

Toroidal devices are the most highly developed. In a simple straight magnetic field, the plasma would be free to stream out the ends. End loss can be eliminated by forming the plasma and field in the closed shape of a doughnut, or torus, or, in an approach called mirror confinement, by "plugging" the ends of such a device magnetically and electrostatically.

Toroidal confinement

The most extensively investigated toroidal confinement concept is the tokamak. The tokamak (an acronym derived from the Russian words for "toroidal magnetic confinement") was introduced in the mid-1960s by Soviet plasma physicists. The magnetic lines of force are helixes that spiral around the torus. The helical magnetic field has two components: (1) a toroidal component, which points the long way around the torus, and (2) a poloidal component directed the short way around the machine. Both components are necessary for the plasma to be in stable equilibrium. If the poloidal field were zero, so that the field lines were simply circles wrapped about the torus, then the plasma would not be in equilibrium. The particles would not strictly follow the field lines but would drift to the walls. The addition of the poloidal field provides particle orbits that are contained within the device. If the toroidal field were zero, so that the magnetic field lines were directed only the short way around the torus, the plasma would be in equilibrium, but it would be unstable. The plasma column would develop growing distortions, or kinks, which would carry the plasma into the wall.



The toroidal field is produced by coils that surround the toroidal vacuum chamber containing the plasma. (The plasma must be situated within an evacuated chamber to prevent it from being cooled by interactions with air molecules.).

In order to minimize power losses in the coils, designs involving superconducting coils have begun to replace copper coils. The plasma in a tokamak fusion reactor would have a major diameter in the range of 10 metres (33 feet) and a minor diameter of roughly 2 to 3 metres. The plasma current would likely be on the order of tens of millions of amperes, and the flex density of the toroidal magnetic field would measure several teslas.

In order to help guide research and development, scientists frequently perform conceptual designs of fusion reactors. One such concept is shown in the figure. This device in theory would generate 1 gig watt (1 billion watts) of electric power—sufficient to meet the electricity needs of a large city.

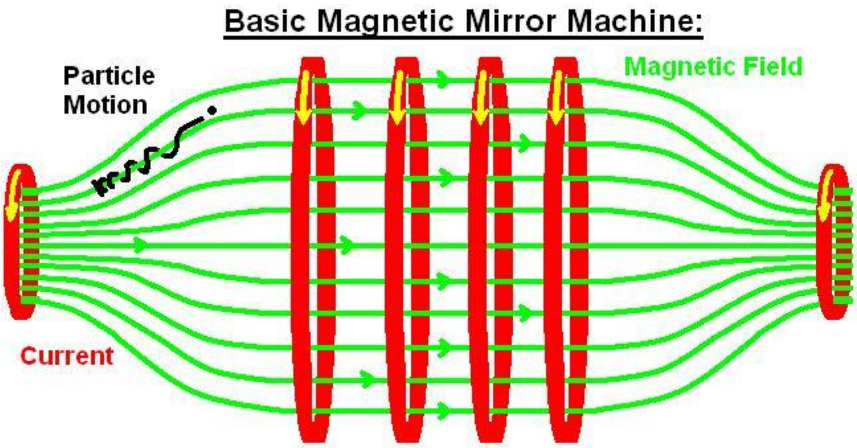
The pilonidal field is generated by a toroidal electric current that is forced to flow within the conducting plasma. Faraday's law of induction can be used to initiate and build up the current. A solenoid located in the hole of the torus can be used to generate magnetic flux that increases over time. The time-varying flux induces a toroidal electric field that drives the plasma current. This technique efficiently drives pulsed plasma current. However, it cannot be used for a steady-state current, which would require a magnetic flux increasing indefinitely over time. Unfortunately, a pulsed reactor would suffer from many engineering problems, such as materials fatigue, and thus other methods have been developed to drive a steady-state current to produce the poloidal magnetic field. A technique known as radio-frequency (RF) current drive employs electromagnetic radiation to generate a steady-state current. Electromagnetic waves are injected into the plasma so that they propagate within the plasma in one direction around the torus. The speed of the waves is chosen to equal roughly the average speed of the electrons in the plasma. The wave electric field (which in a plasma has a component along its direction of travel) can then continuously accelerate the electrons as the wave and particles move together around the torus. The electrons develop a net motion, or current, in one direction.

Another established current-drive technique is neutral-beam current drive. A beam of high-energy neutral atoms is injected into the plasma along the toroidal direction. The neutral beam will freely enter the plasma since it is unaffected by the magnetic field. The neutral atoms become ionized by collisions with the electrons. The beam then consists of energetic positively charged nuclei that are confined within the plasma by the magnetic field. The high-speed ions travel toroidally along the magnetic field and collide with the electrons, pushing them in one direction and thereby producing a current. Both RF and neutral-beam current-drive techniques have a low efficiency (i.e., they require a large amount of power to drive the plasma current). Fortunately, a remarkable effect occurs in tokamak plasmas that reduces the need for external current drive. If the plasma pressure is greater in the core than at the edge, this pressure differential spontaneously drives a toroidal current in the plasma. This current is called the bootstrap current. It can be considered a type of thermoelectric effect, but its origin is in the complex particle dynamics that arise in a toroidal plasma. It has been observed in experiments and is now included routinely in advanced experiments and in tokomak reactor designs.

Other toroidal confinement concepts that offer potential advantages over the tokamak are being developed. Three such alternatives are the stellarator, reversed-field pinch (RFP), and compact torus concepts. The stellarator and RFP are much like the tokamak. In the stellarator the magnetic field is produced by external coils only. Thus, the plasma current is essentially zero, and the problems inherent in sustaining large plasma current are absent. The RFP differs from the tokamak in that it operates with a weak toroidal magnetic field. This results in a compact, high-power-density reactor with copper (instead of superconducting) coils. Compact tori are toroidal plasmas with no hole in the centre of the torus. Reactors based on compact tori are small and avoid the engineering complications of coils linking the plasma torus.

Mirror confinement

An alternative approach to magnetic confinement is to employ a straight configuration in which the end loss is reduced by a combination of magnetic and electric plugging. In such a linear fusion reactor the magnetic field strength is increased at the ends. Charged particles that approach the end to slow down, and many are reflected from this "magnetic mirror." (The same magnetic reflection mechanism traps particles in the Earth's magnetosphere, specifically in the Van Allen radiation belts.)



Unfortunately, particles with extremely high speed along the field are not stopped by the mirror. To inhibit this leakage, electrostatic plugging is provided. An additional section of plasma is added at each end beyond the magnetic mirror. The plasma in these “end plugs” produces an electrostatic potential barrier to nuclei. The overall configuration is called a tandem mirror.

4.Plasma applications

Because of its diverse nature plasma finds application in various fields such controlled thermonuclear fusion, surface treatment, biomedical applications, lighting, medicine, electronics, transportation and space propulsion, display technology, space physics, solid state plasma, gas lasers, etc. Some of the important and interesting applications of plasma in various fields are discussed here. Some of the Plasma applications for both the industries as well as individual users are as follows:

1-Pollution Treatment

Diesel engines are used in a different application like in transportation, power generation, farming, construction and in other industrial settings. They produce a significant amount of pollution, especially NO_x. NO_X storage reduction, Selective NO_X recirculation and Non-thermal Plasma have been considered increasingly in recent times, with a view to developing techniques to reduce NO_X emissions in diesel engine. Non-thermal Plasma technology has been introduced as a promising method of NO_X removal which is done by reaction with free electrons, ions, radicals, molecules in Plasma.

2 Liquid radioactive waste utilization

Plasma technology can be used for the utilization and neutralization of liquid radioactive waste. The most difficult phase of the nuclear fuel cycle is safe disposal or recycling. This requires separation and extraction of different components to regenerate the irradiated fuel, and neutralization of waste before disposal. The irradiated fuel is around 97% and waste is around 3%, which consists of U235and radioactive isotopes of plutonium.

3 Semiconductor Processing

Today about a hundred chips are made from a silicon wafer of 4-8-inch diameter. The element forming these chips should be around 0.25 micrometer [19]. This resolution is only possible with Plasma. The Plasma helps in the process of etching in following ways

a) Atomic species such as fluorine or chlorine are produced using Plasma which in turn perform the etching

b) A substrate is produced by using Plasma so that the etchant species act in an effective manner.

c) Plasma helps to keep the process of etching in a straight line due to its highly directional properties

4. Ion Implantation

Ion implantation is a process in which the acceleration of ions towards the targets occurs at high energies to enter them below the surface of the target that usually depends on the acceleration energies and the applications for which it is used. Ion implanters are used for the manufacturing of modern integrated circuit (IC) by modifying silicon or doping several other semiconductors. It includes the production of an ion beam and it is steering into the substrate in order to make the ions to come to rest under the surface.

The beamline at energy causes the ions to move at which they were taken out from the source material or energy at which they are decelerated or accelerated by radio frequency or dc electric fields.

5. Living Tissues Treatment

The Cold Plasma treatment initially dedicated to environmental protection has been completed in the last years with bio-medical and bio-decontamination treatments. The living tissue treatment imposes characteristics for the devices used to produce cold Plasma such as;

a) To avoid the electrocution.

b) Reduction of invasive actions on living cells.

c) Assuring the selectivity to affect only the afflicted cells.

d) Avoiding the thermal effect.

e) Limitation of treatment time to avoid the induction of toxic effects to treat cells.

Vii. Use of Plasma in Treatment of Prostate Cancer

In the early days, curing cancer was a matter of early detection and timely treatment of the tumors. The side effects of techniques used to treat the cancerous cells were quite a few including the damaging of body cells without the assurance about the complete elimination of cancer

Low-temperature Atmospheric Plasma has revolutionized the field of medicine and is being successfully used to cure cancer. It has low side effects than the conventional techniques and the chances of cancer returning to the body are minimal. The reason is that the low-temperature plasma breaks down the DNA double strands within the nucleus of Prostate cancer

The device uses 6kV supply at 30 kHz frequency. Helium gas is used with 0.3 % of Oxygen gas mixed with it. The distance of the plume is 10mm from body to nozzle and the time of operation is usually 5 to 10 minutes. Body temperature does not go above 36.5oC during that period

6. High Energy Density Pinch Plasma

The synthesis of different characteristics Nano-scale materials have many optimizations and improvement processes and routes, including vapor reduction and milling, chemical and nature's organic routes. Low-temperature (cold) Plasmas have temperature and density very smaller than high-density (hot) pinch and fusion

plasma. Very high temperatures present in pinch and fusion plasma can produce the fully ionized material, while the low-temperature Plasmas is produced by DC or AC energization of working gas, radio-frequency or microwave electromagnetic fields. Such discharge level has a low level of ionization and most of the ions still exist in the neutral state, having the energy of few tens of electron volts that use kinetic temperatures of an electron to produce Nano-materials. Low-temperature plasmas are many times preferable for use in nanotechnology applications. These can be further classified as non-equilibrium (non-thermal) and equilibrium (thermal) Plasmas. The Non-equilibrium plasma follows the relation of Te >>Ti = Tg. Where Tg, Te, Ti and are corresponding temperatures of background gas, ions and electrons. These values are dependent on kinetic energies. Generation Process of non-equilibrium thermal Plasmas are followed:

a) Low operating pressure technique which results in less frequent collisions between neutral, ion and electrons and hence they cannot achieve thermal equilibrium.

b) The high-pressure techniques used along with pulse discharge. The collisions are high but for short time, so the thermal equilibrium cannot be reached due to pulse discharge interruption.

c) The high-pressure micro-plasma is high-pressure plasma whose dimensions reduced to micron size, which causes enormously increase in electrons kinetic energy due to the high electric field.

The equilibrium (thermal) Plasmas are in thermal equilibrium where temperature equilibration made by an electron, ions and neutral repeated collision in high-pressure plasma discharges results in the substantial degree of ionization due to Te=Ti=Tg. Both equilibrium and non-equilibrium techniques have been widely used in Plasma Nano-technology. The thermal, chemical and electrical properties of low-temperature Plasmas provide an efficient and versatile tool for nanotechnology.

7 Cutting by Plasma

Plasma cutting is a process that cuts through electrically conductive materials by means of an accelerated jet of hot plasma. Typical materials cut with a plasma torch include steel, stainless steel, aluminum, brass, and copper, although other conductive metals may be cut as well. Plasma cutting is often used in fabrication shops, automotive repair and restoration, industrial construction, and salvage and scrapping operations. Due to the high speed and precision cuts combined with low cost, plasma cutting sees widespread use from large-scale industrial applications down to small hobbyist shops. The basic plasma cutting process involves creating an electrical channel of superheated, electrically ionized gas i.e. plasma from the plasma cutter itself, through the workpiece to be cut, thus forming a completed electric circuit back to the plasma cutter through a grounding clamp. This is accomplished by a compressed gas (oxygen, air, inert, and others depending on the material being cut) which is blown through a focused nozzle at high speed toward the workpiece. An electrical arc is then formed within the gas, between electrodes near or integrated into the gas nozzle and the workpiece itself. The electrical arc ionizes some of the gas, thereby creating an electrically conductive channel of plasma. As electricity from the cutter torch travels down this plasma it delivers sufficient heat to melt through the workpiece. At the same time, much of the high-velocity plasma and compressed gas blow the hot molten metal away, thereby separating, i.e. cutting through.

8 Plasma Etching

Sputtering or ion milling is used for etching, the item that is being etched is kept on one side of the electrode of the system. Ions are accelerated by DC radio frequency or microwave electric field. To increase Plasma density, a magnetic field is used. We can also use inert gasses or reactive gasses for this purpose.

Plasma that is generated from RF has a frequency ranging from kHz to GHz. Plasma is produced from the region that is empty of the substrate and then defused so that it doesn't cause any harm to the substrate by high energy electron.

Plasma et ching is used in silicon dioxide for making memory devices. Plasma gives high-ranking results for chemical etches (especially wet) . Numbers of gasses are used for Plasma etching some of them are SF6, CF4, Halogen mixtures (CF4 /O2). The Plasma has the ability to break these gasses into reactive ions, neutrals or free radicals then they interact with the substrate as they both play their role in etching, especially neutrals. Reactive Ion Etching (RIE) tools are given in Figure below.