DISSERTATION

On

Effect of Dust Charge Fluctuations on Lower Hybrid Instability in Tokamak in Presence of Neutral Beam & Magnetic Shear

Submitted By

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CERTIFICATE

This is to certify that work which is being presented in the dissertation entitled **Effect of Dust Charge Fluctuations on Lower Hybrid Instability in Tokamak in Presence of Neutral Beam & Magnetic Shear** is the authentic work of **Sumit Kumar** under my guidance and supervision in the partial fulfillment of requirement towards the degree of **Master of Technology in Nuclear Science & Engineering** run by Department of Applied Physics in Delhi Technological University during the year 2013-2015.

As per the candidate declaration this work has not been submitted elsewhere for the award of any other degree.

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DECLARATION

I, **Sumit Kumar**, hereby declare that the work entitled **"Effect of Dust Charge Fluctuations on Lower Hybrid Instability in Tokamak in Presence of Neutral Beam & Magnetic Shear"** has been carried out by me under the guidance of **Prof. S.C. Sharma**, at Delhi Technological University, Delhi. This dissertation is part of partial fulfillment of requirements for the award of degree of M.Tech in Nuclear Science & Engineering. This is the original work and has not been submitted for any other degree in any other university.

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ABSTRACT

A neutral beam propagating through a magnetized dusty plasma drives lower hybrid waves to instability via Cerenkov interaction. A dispersion relation and the growth rate of the instability for this process have been derived taking into account the dust charge fluctuations.

The frequency and the growth rate of the unstable wave increases with the relative density of negatively charged dust grains. Also, as the dust grain parameters are varied the growth rate also varies. When the dust grain size is increased the growth rate decreases. Moreover, the growth rate of the instability increases with beam density and scales as the one-third power of the beam density. In addition, when the dust density increases, the growth rate decreases.

CHAPTER 1

INTRODUCTION

1.1 WHAT IS PLASMA?

Plasma is an ionized gas which is the fourth state of matter. A liquid state is formed by the sufficient heating of any solid such that the thermal-motion of the atom breaks the crystal-lattice structure apart. When the liquid is sufficiently heated, a gas is formed such that atoms get vaporized off the surfaces much faster than they re-condense. Plasma is formed when the gas is heated sufficiently such that the collision between atoms knock off their electron in the process. Between plasma & very weakly-ionized gas a transition which occurs is a matter of nomenclature. The important fact about plasma, an ionized-gas, is its unique properties. The forces between near neighbour region of the material determine the dynamics of motion in most materials. Electric fields in plasma arise from the separation of charges between electrons & ions. Also, magnetic fields and current arise from charged particle flows. These magnetic and electric fields result in a range of phenomena of startling-complexity, of considerable practical-utility, 'action at a distance', and sometimes of great beauty [1].

1.2 NATURAL PLASMA

As it is estimated more than 99 percent of natural plasma dominate earth's environment in the solar system and farther out in the interstellar space. Some naturally occurring plasma phenomenon can be found close to the earth's surface**.**

1.2.1 SPACE PHYSICS AND PLASMA

Solar wind - Designates the flux of charged particles emitted by the strong activity in the sun. When these particles impinge the magnetosphere (a region in which the configuration of the earth's magnetic field lines remains relatively constant) they are stopped and deflected, creating a shock wave structure which is filled with plasma.

Ionosphere - A plasma weakly ionized by the radiation from the sun, which extends from an altitude of 50 km to 10 earth radii with variable density and temperature (10^9 to 10^{12} charged particles/m^3, 10^2 to 10^3 K).

Van Allen radiation belts - High energy particles trapped in the magnetic field of the earth which was discovered by James Van Allen in 1958. From the observations of the earlier earth satellite, they indicate the beginning of modern space physics investigation.

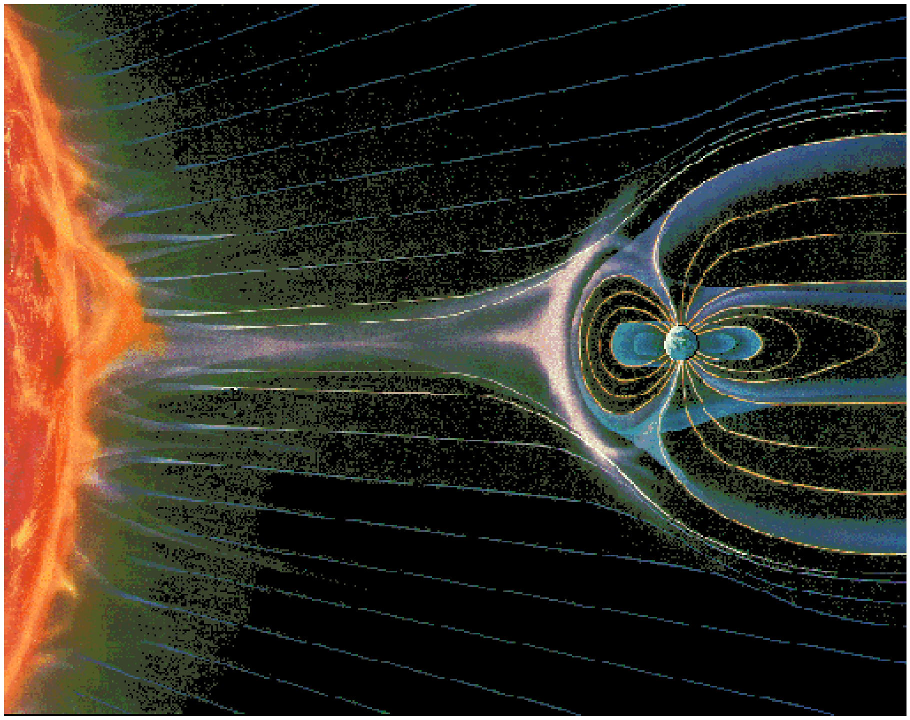

Fig.1.1 Solar wind [8]

1.2.2 ASTROPHYSICS AND PLASMA

Astrophysics involves the physics of stellar phenomena which under extreme conditions are rich is plasma. Few examples of astrophysical-plasma mentioned below are:-

Stellar interiors and atmospheres – Stellar interiors are sufficiently hot to be in a plasma state even for very high particle densities (10^{33} charged particles /m^3, $3x10^7$ K). Thermonuclear reactions which occurs in the high-density solar core (10^{31} charges particles/m^3, $1.5x10^7$ K) are responsible for the radiation from the sun. The solar corona is a plasma with comparatively low values of the density and temperature (10^{10} to 10^{14} charged particles/m^3, 10^3 to 10^6 K) that increases considerably during a solar flare (10^{14} to 10^{18} charged particles/m^3, 10^6 to 10^7 K)

Interstellar medium – It is a cold hydrogen plasma that exists due to very low density, and consequently low recombination rate (10^3 to 10^4 charged particles/m^3, 10^2 K).

Evolution of galaxies, cosmic rays acceleration, & strong radiation sources (pulsars, nebulae) – These phenomena are studied in modern astrophysics using a variety of plasma theories.

Fig.1.2 A stellar phenomenon [9]

1.2.3 NATURAL PLASMA AND EARTH

The occurrence of plasmas close to earth surface is limited. Life only can exist in less than 1% of the universe in which plasma don't occur naturally. Examples of the two most well known natural plasma observed from the surface of earth mentioned below are:-

Auroras– These are visible glows which are a consequence of the excitation of atmospheric atoms & molecules, that are bombarded by charged-particles which are evicted from the sun & are deflected by the geomagnetic-field.

Fig.1.3 Aurora phenomenon [10]

Lightning – This is a high current (tens to hundreds of kA) transient electric discharges which occur in the atmosphere with an ordinary extension of a few kilometers. The external source responsible for the generation of lightning is associated to the electrodynamics of the atmosphere [2].

Fig. 1.4 Lightning phenomenon [11]

1.3 PRODUCTION OF PLASMAS

A plasma can be produced by raising the temperature of a substance until a reasonably high fractional ionization is obtained. The degree of ionization and the electron temperature are closely related under thermodynamic equilibrium conditions. This relation is given by the Saha equation. Although plasmas in local thermodynamic equilibrium are found in many places in nature, as is the case for many astrophysical plasmas although they are not very common in the laboratory.

Plasmas can be generated by ionization processes also that raise the degree of ionization much above its thermal equilibrium value. There are many different methods of creating plasmas in the laboratory and, depending on the method, the plasma may have a high or low density, high or low temperature, it may be steady state or transient, stable or unstable, and so on. In what follows, a brief description is presented of the most commonly known processes of photo-ionization and electric discharge in gases.

Ionization occurs by absorption of incident photons in the case of photo-ionization, in which energy is equal to or greater than the ionization potential of the absorbing atoms. The excess energy of the photon is transformed into kinetic energy of the electron-ion pair formed. For example, the ionization potential energy for the outermost electron of atomic oxygen is 13.6 eV, which can be supplied by radiation of wavelength smaller than about 910 A° i.e. in the far ultraviolet. Ionization can also be produced by X-rays or gamma-rays, which have much smaller wavelengths. The Earth's ionosphere, for example, is a natural photo-ionized plasma.

In a gas discharge, an electric field is applied across the ionized gas, which accelerates the free electrons to energies sufficiently high to ionize other atoms by collisions. One characteristic of this process is that the applied electric field transfers energy much more efficiently to the light electrons than to the relatively heavy ions. The electron temperature in gas discharges is therefore usually higher than the ion temperature, since the transfer of thermal energy from the electrons to the heavier particles is very slow.

When the ionization source is turned off, the ionization decreases gradually because of recombination until it reaches an equilibrium value consistent with the temperature of the medium. In the laboratory the recombination usually occurs so fast that the plasma completely disappears in a small fraction of a second [3].

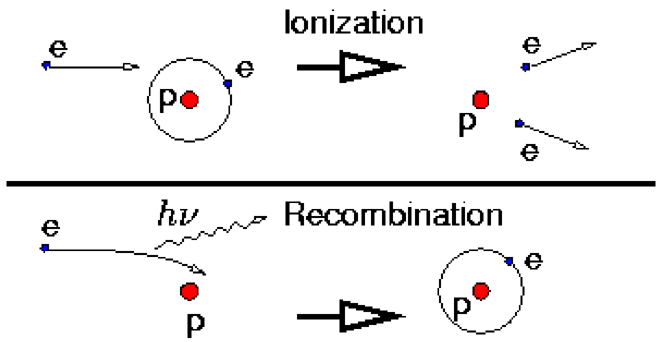

Fig. 1.5 Ionization and recombination [12]

1.4 APPLICATION OF PLASMAS

Most practical and important applications of plasma lies in future. The major method in practice for generating electric power is to use sources of heat to get steam from water, which drives turbo generators. Sources of heat depend on the combustion of oil, coal, and natural gas (all fossil fuels), and on the fission process in the a very high amount of heat-energy of H-atom, He-atom & the neutrons. By absorbing those products in a surrounding medium, a powerful heat source could be created. To realize a net power output from such a generating station—allowing for plasma radiation and particle losses and for the somewhat inefficient conversion of heat to electricity—plasma temperatures of about 100,000,000 K and a product of particle density times containment time of about 10^{20} seconds per cubic metre are necessary. For example, at a density of 10^{20} particles per meter cubed, the containment time must be one second. Such figures are yet to be reached, although there has been much progress.

Fusion reactor may also desalinate seawater in addition to generating power. Around 66.67% of the land surface in the world is uninhabited, of which 50% of the area is arid. The use of both giant fusion and fission reactors in evaporating the seawater on large scale can make irrigating such arid areas economically viable. The elimination of the heat-steam-mechanical energy chain is another possibility in power-production. One of the suggestions here depends on the effects of dynamo. If a plasma moves perpendicular to a magnetic field, an electromotive force, according to Faraday's law, is generated in a direction perpendicular to both the direction of flow of the plasma and the magnetic field. This dynamo effect can drive a current in an external circuit connected to electrodes in the plasma, and thus electric power may be produced without the need for steam-driven rotating machinery. This process is referred to as magneto-hydro-dynamic (MHD) power generation and has been proposed as a method of extracting power from certain types of fission reactors. Such a generator powers the auroras as the Earth's magnetic field lines tap electrical current from the MHD generator in the solar wind.

For accelerating plasma, thermo effect which is the inverse of the dynamo into plasmas, it is possible achieving thrust that is directly-proportional to the square of magnetic-field. For the propulsion of spacecraft in deep-space motors, based on such techniques have been proposed. The advantages of using such motors is that they can achieve very high exhaust-velocities, thus it will minimize fuel consumption.

Glow discharge is another practical application of plasmas which occurs between two electrodes at pressure of 1/1000 bar. The light given off by neon-tube & other such light sources like fluorescent-lamps are examples of glow discharges phenomenon, which is produced during electric discharge resulting into plasma production. Ionization degree in such plasmas are generally low, but density of electrons in range of 10^{16}-$10^{18}m^{-3}$ can be achieved with temperature of electron at 10^5K. In a region near the cathode, ionization leads to the production of current flow, with major potential-difference occurring there between the electrodes. The plasma is not contained in this region, but in the region between it & the anode i.e., the positive-electrode.

Other applications of the glow discharge include electronic switching devices; it and similar plasmas produced by radio-frequency techniques can be used to provide ions for particle accelerators and act as generators of laser beams. As the current is increased through a glow discharge, a stage is reached when the energy generated at the cathode is sufficient to provide all the conduction electrons directly from the cathode surface, rather than from gas between the electrodes. Under this condition the large cathode potential difference disappears, and the plasma column contracts. This new state of electric discharge is called an arc. Compared with the glow discharge, it is a high-density plasma and will operate over a large range of pressures. Arcs are used as light sources for welding, in electronic switching, for rectification of alternating currents, and in high-temperature chemistry. Running an arc between concentric electrodes and injecting gas into such a region causes a hot, high-density plasma mixture called a plasma jet to be ejected. It has many chemical and metallurgical applications [4-7].

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CHAPTER 2

TOKAMAK

2.1 WHAT IS FUSION?

"Fusion" plays a prominent role in the existence of Universe. It has scientific importance which helps in sustaining one's life on earth.

Therefore, we can define fusion in our own words as "an important action that takes place inside the core of the sun," that we can observe and see clearly as light & feel the warmth, which is the outcome of a fusion reaction. During the process, hydrogen-nuclei become incompressible, or in other word we can say that when hydrogen-nuclei strike together with great force, it starts fusing into heavier He-atoms and starts releasing enormous energy.

The optimal condition for fusion to take place has been created in the universe by the gravitational-forces in action. Billions of years ago, the hydrogen-clouds of early universe gathered together into gargantuan stellar-bodies under the effect these forces. Fusion occurs inside their core, where the density & temperature is extremely high.

Fig.2.1 Fusion occurring in the core of the Sun & stars [8]

2.2 HOW FUSION PRODUCES ENERGY?

This is a known fact that nothing in this universe is constant, it's only because atom never stagnates. While absorbing energy it becomes hotter slowly & the atom starts moving rapidly. When these atoms are more hot, they will move at even higher speed i.e, the hotter they are the faster they move & are always in motion. The temperature inside the core of the sun is around $15x10^{6}$ °C. At this high speed, the hydrogen-atom remains in the condition of agitation always. When the atoms fuse, they overcome the natural electrostatic repulsion offered by the positive charges which exists between the nuclei. Helium-atom is formed when, there is a fusion of two lighter hydrogen-atoms (H: H).

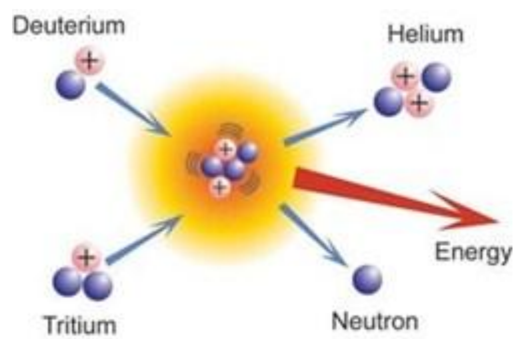

Fig.2.2 A schematic of fusion reaction [9]

The mass which results in He-atom is exactly not the sum of initial two H-atoms, the mass defect results into the release of large amount of energy which is given by Einstein's formula $E=mc^2$, where 'm' denotes the lost mass & 'c' denotes the speed of light.

Every second, sun consumes six-hundred million-tons of hydrogen (H_2) to produce helium (He), thus releasing enormous energy.

Achieving fusion needed a different approach on Earth due to the absence of the benefits of gravitational-forces which are at work in our universe.

2.3 FUSION ON EARTH

In 20th-century fusion-science has identified the most effective fusion-reaction which can be reproduced in the lab setting- the reactions between the two isotopes of hydrogen: deuterium(D) & tritium(T). At the 'lowest' temperatures, this D-T fusion-reaction produces the maximum energy-gain. It requires temperatures of about $15x10^7$ °Celsius for fusion to take place which is 10 times more than the H-H reaction taking place inside the core of the sun.

Electrons get separated from their nuclei at very high temperatures and a hot, electrically-charged plasma gas is formed. Inside a fusion-device, plasma provides the needed environment where lighter elements fuse & yield energy as happens inside a star.

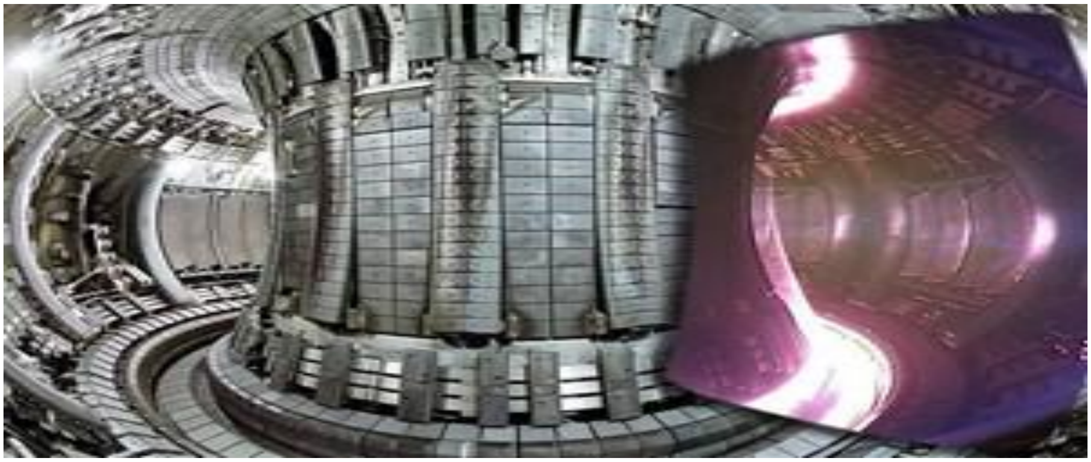

Fig.2.3 European JET Tokamak [10]

In ITER, the fusion reaction will be achieved in a tokamak device that uses magnetic fields to contain and control the hot plasma. The fusion between deuterium and tritium $(D-T)$ will produce one helium nucleus, one neutron, and energy.

This helium nucleus carries an electric charge which will interact with the magnetic fields of the tokamak and remain confined within the plasma. However, around 80 percent of the energy produced is carried away from the plasma by the neutron which has no electrical charge and hence unaffected by magnetic fields. The neutrons will be absorbed by the surrounding walls of the tokamak, transferring their energy as heat to the walls.

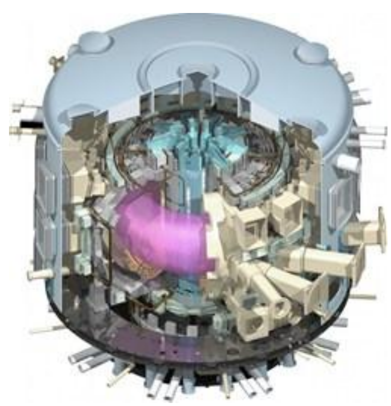

Fig.2.4 ITER Tokamak [11]

In ITER, this heat will be dispersed by cooling-towers. In the upcoming fusion-plant prototype DEMO & in future industrial fusion installations, the heat from the ITER will be used to produce steam and with the help of alternators & turbines to produce electricity [1].

2.4 WHAT IS A TOKAMAK?

A tokamak is a device which confines plasmas in the shape of a torus with the help of magnetic-fields. For achieving a state of equilibrium, a stable-plasma needs magnetic-field lines which move in a helical-shape around the torus. Such helical-field can be produced by introducing a toroidal-field & a poloidal-field. In a tokamak, the electro-magnets which surrounds the torus produces the toroidal-field & due to toroidal electric current which flows inside plasma results in toroidal-field. This toroidal current is introduced in the plasma by using a second set of electromagnets.

Tokamak is among one of the different types of magnetic-confinement devices available and for obtaining controlled-fusion power, it is one of the most researched candidate. Magnetic-fields are usually used for confining as no solid materials can cope with the extremely high temperatures of plasma. Stellarator can work as an alternative to the tokamak.

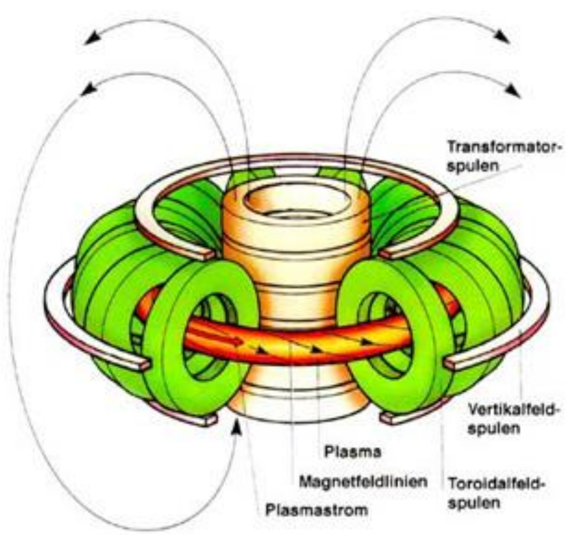

Fig.2.5 Schematic diagram of a tokamak [12]

2.5 A BRIEF HISTORY OF TOKAMAK

Although research on nuclear-fusion began immediately after the end of World-War 2, many countries then classified their research as secret. The damage related to tokamak is often large but is rarely dramatic. After United Nation's 1955 resolution declassified & international scientific collaborations started taking place in ITER.

Experiments & researches on tokamak system commenced in 1956 at Kurchatov Institute in Moscow led by Soviet scientists headed by Artsimovich. These scientists developed the 1st tokamak whose most successful version was T3 and its larger version was T4. In 1968, T4 was tested which was the 1st ever quasi-stationary thermo-nuclear fusion-reaction in Novosibirsk [3].

At the 3rd international IAEA conference in Novosibirsk on Plasma Physics & controlled-nuclear fusion research, scientists from the Soviet Russia confirmed that they have achieved electron temperature of 1000 eV in their tokamak device. Initially American and British scientists took this news as mere hype but later they too confirmed the findings by using tests done with the help of laser scattering machines.

2.6 TOROIDAL DESIGN

Negatively charged-electrons and negativly & positvely charged-ions in a fusion-plasma are at extremely high temperatures, and hence have correspondingly higher velocities. For maintaining fusion process particles derived from the hot-plasma must be constrained within the central-region, else the plasma will cool rapidly. In the fusion devices, magnetic-confinement exploits the fact that charged particle in a magnetic-field experiences a Lorentz-force & follows a helical path along the lines of magnetic field.

In earlier devices, fusion used to produce a poloidal-magnetic field to confine the plasmas along the linear-axis between the two points. Later researchers found that a simple toroidal-field, where lines of magnetic field run in circle along the axis of symmetry and contains plasma rarely better than that in the absence of field altogether. By looking at the orbit of the individual particles, it can be easy understood. The particles both spiral around the lines of field as well as drifts across the field. As a toroidal-field is curved & whoe strength reduces while moving away from the rotational-axis, the ions & electrons move parallel to this axis, but in directions opposite to original one. For both ions & electrons separation of charge leads to electric-field & additional drift, away from the axis of rotation. Plasma alternatively, can be seen as a torus filled with fluid with a frozen magnetic-field. The pressure exerted by plasma results into a force which tries expanding the torus. Outside plasma, the magnetic-field cannot prevent such expansion. The plasmas simply slip between the lines of magnetic-field.

To be efficiently confined by magnetic-field in case of a toroidal-plasma, there must be a twisting field-lines. There are no longer flux-tubes available which simply encircles the axis, but, in case there is enough symmetry in twist, flux will come into play. Some plasmas in the flux-surface will be present on the outside or on low field side of the torus & will try to drift to other flux surfaces which are further away from the circular-axis of the torus. The other part of the plasmas will lie on the inside of the flux surface say on higher-field side. Since an inward drift compensates some of the outward-drift on the same flux-surface, an equilibrium is established though on a macroscopic level but with much improved confinement. To analyze the effect in another way is by twisting the field-lines such that the electric-fields between top & bottom of torus which tends to bring the outward drift, gets shorted out due to the presence of field-lines connecting the top to bottom.

When we look into the problem from close, the need for a vertical-component of magnetic-field arises which is parallel to the axis of rotation. The toroidal-plasma current in the vertical-field generates the inward force due to Lorentz force which is holding the plasma torus in equlibrium.

When large toroidal-current is set-up, the devices tends to suffer the stability problem. The non-linear evolution of magneto-hydro dynamical instabilities leads to quenching of the plasma-current in a dramatically short time scale which is of the order of the milli-second. Highly energetic electrons are produced which are also called runaway-electrons & a global confinement loss is achieved finally. In a small area very high energy is concentrated. Such a phenomenon is called a major disruption. The number of major disruption which happened during the operation of tokamak has always been rather high and of the scale of few % of the total numbers of the shots. In tokamaks that are operated presently, the damage is many times large but are not dramatic in majority of the time. It is anticipated that the occurrence of a limited number of major disruptions in the ITER tokamak will most probably damage the chamber of the device with no possibilities to restore it.

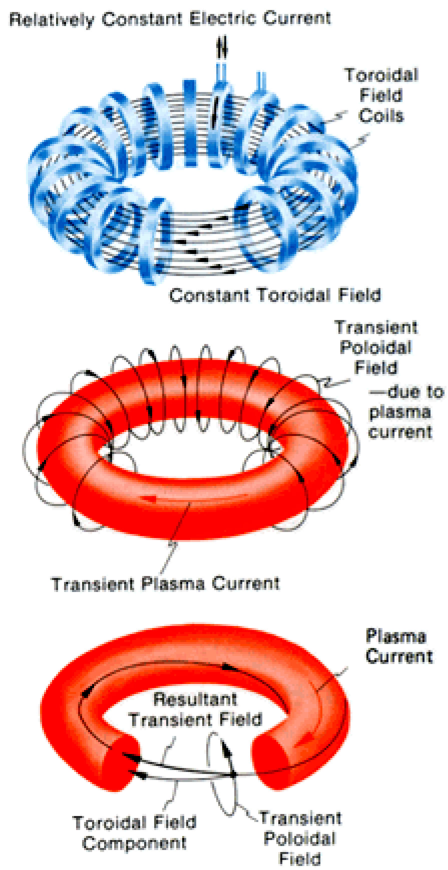

Fig.2.6 Magnetic field and current in tokamak [13]

2.7 PLASMA HEATING

In operating fusion based reactor, when a fresh D-T mixture is introduced, a portion of the enrgy produced will be utilized in maintaining the temperature of plasma. However, during the starting of a reactor the plasmas need to be heated to its operating temperature which is around 100M Celsius or higher than 10keV. At present operational tokamak under magnetic-fusion experiments, fusion energy which is being obtained is insignificant for maintaining the plasma-temperature.

2.7.1 RESISTIVE OR OHMIC HEATING

Plasmas being electrical conductors, by inducing current to it, it is possible to heat plasmas . In fact, this induced-current which helps in heating plasmas generally generates majority of the poloidal-field. Thus, the plasma could be viewed as the secondary-winding of a transformer where the current get induced when the current in the electromagnetic-winding is slowly increased that is linked with the plasma torus. It is inherently a pulsed-process as there is a limit to current flowing through the primary winding. Hence, tokamaks must either rely on the other means of heating and current-drive or operate for a shorter period of time. This induced current results into heating of plasma and is also known as resistive or ohmic-heating. This heating is similar heating which occurs in an electric-light bulb or in an electric-heater. The heat produced depends on the degree of electric-current passing through plasma & the resistance which is offered by plasma. But with the rise in plasma temperature the resistance falls & effectiveness of ohmic-heating decreases. As it appears, the highest temperature of plasma that can be achieved using ohmic-heating in the tokamak is around 25million degree-Celsius. In case still higher temperature is needed, additional methods of heating must be used.

2.7.2 NEUTRAL BEAM INJECTION

Introducing rapidly-moving or a high-energy atoms into ohmically or resistively heated magnetically-confined plasma results into the injection of neutral beam in plasma. Due to the magnetic-field, the atoms ionize & get trapped as the they pass through the plasma. In repeated collisions these high-energetic ions transfer part of their energies to the particles in plasma, thereby increasing the plasma-temperature.

2.7.3 MAGNETIC COMPRESSION

By using a technique of sudden compression, a gas can be heated. In similar fashion, by increasing the magnetic-field confinement while compressing the plasma fast, the plasma-temperature is increased. In a tokamak device system such compression is obtained simply by running plasma in a region with larger magnetic-field. As this plasma compression brings the ion closer, this process has got an additional benefit of aiding attainment of density required for a fusion reactor.

2.7.4 RADIO-FREQUENCY HEATING

Outside torus, a high frequency electromagnetic-wave can be produced with the help of oscillators. In case the waves are provided with the correct frequency or wavelength & polarization, their energies are transferred to the charged-particles of bulk plasma. Several other techniques do exist including that of ion-cyclotron resonance heating & electron-cyclotron resonance heating. Generally, energy produced by such method are transferred with the help of microwaves.

2.8 TOKAMAK COOLING

The spiraling plasma inside a tokamak reactor during fusion reaction produces large numbers of highly energetic-neutrons. As these neutrons are electrically-neutral, they are captivated no longer inside the stream of plasma by the toroidal-magnets & continue unless they are stopped by the inside walls of the tokamak. These freed-neutrons facilitate a simpler way to absorb heat from the plasma-stream which is a large plus-point of tokamak reactors; this is how the fusion-reactors produce usable energy. Tokamak's inner wall must be cooled as these neutrons attains high energy which can melt the walls of the reactor. A cryogenic system is therefore employed to prevent any heat-loss from the super-conducting magnets. Refrigerants like liquid-nitrogen or liquid-helium are used in most cases. Plates made of ceramic designed specifically to withstand very high temperatures are placed on inner walls of reactor so as to protect the reactor and the magnets [2].

2.9 PLASMA CONFINEMENT

Physicists since 60s have been exploiting the properties of plasmas in tokamak-devices. A major break-through was achieved in plasma-science at the time when the doughnut-shaped torus of the tokamak came into existence where temperature levels & plasma-confinement time reached such levels that had never been achieved earlier.

The chamber of ITER tokamak will be twice larger in volume than the earlier tokamaks with plasma-volume of $830m^3$. Towards the left, all the space in the chamber will be occupied by plasma, though no material can withstand the extreme-temperature of plasma. By exploring the plasma properties, now scientists are able to contain or confine plasma away from the walls of the tokamak.

Plasma consists of charged particles which can be shaped & confined by magnetic-forces. As iron-filings align themselves in presence of magnet likewise plasma-particles will also follow the lines of magnetic-field. Like ordinary solid-container, the magnetic-field acts like a recipient and is unaffected by heat.

Different types of magnetic-fields in ITER will work in subtle combination to give shape to plasma either into the form of a torus or ring which will isolate hot-plasma from relatively cooler vessel walls to maintain the energy for longer period of time possible. First safety in confinement-barrier is the vacuum vessel which should not come in contact with plasma [3].

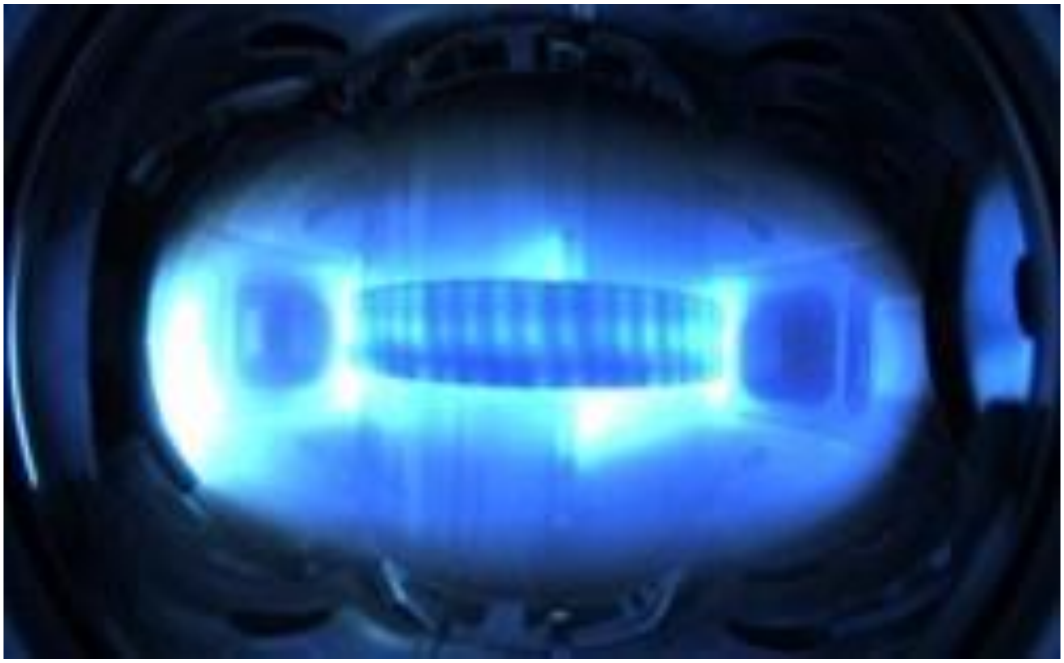

Fig.2.7 Magnetically confined plasma in KSTAR [14]

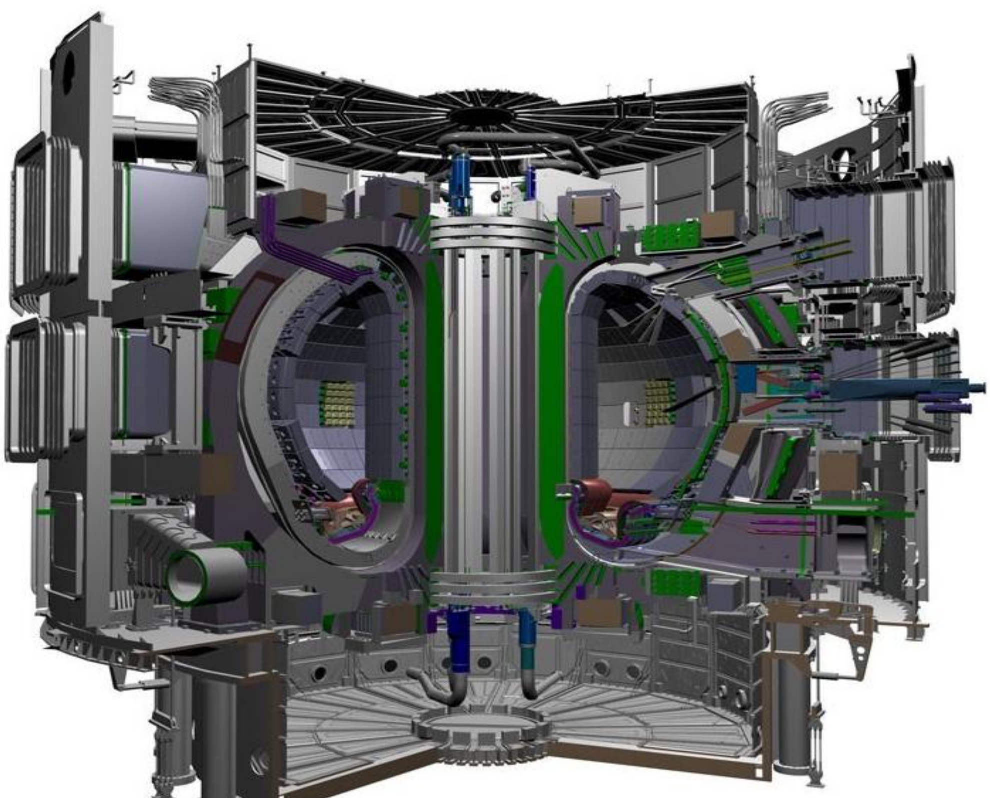

Fig.2.8 ITER, the world's largest Tokamak [15]

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CHAPTER 3

ROLE OF DUST GRAINS IN TOKAMAK

3.1 INTRODUCTION

As we know that in magnetic-confinement of fusion devices, small particles exist [1], for instance if after some time of operation of tokamak, its bottom area is cleaned, one can collect fine grain materials. On wiping with a clean cloth on vertical surfaces leaves black stains on clothes indicating dust. The complex system of a fusion device because of dust consequences on the device & its thermonuclear which need to be addressed are just the beginning [2–4]. Safety aspects related to plasma-operation & its performance and thus the safety of the thermonuclear fusion reactor can be easily distinguished. Works related to the 1st aspect has gained a significant and crucial impact from ITER [5] project, whereas about the 2nd aspect; practically nothing is known.

Inventory of a dust-bound tritium(T) is the current concern about the reactor's safety in future. Since dust-bound tritium is not reprocessed in the tritium separation & reprocessing-loop hence, it increases the inventory of the site. In case of severe accidents, dust may also become a vehicle making tritium mobile. An explosion hazard can be considered as further aspect which can exist when gushing out from a broken cooling-line gets into contact with the highly dispersed carbon emanating H_2 and CO. When the amount of H2 is sufficiently large enough, it can combine with oxygen in the environment to form an explosive-mixture.

Another aspects are basically engineering issues where the large dust quantities are accumulating at the bottom of the fusion-device. A loose dust layer may block the transfer of heat to cooling-towers & may block gaps as well which were specifically designed with purpose, example, for electrical insulation or thermal-expansion reasons. These dust layers may sublime easily when they are exposed to very high amount of heat. At one hand, this can lead to a source of impurities in the plasma which, at the other hand can boost shielding protection of the surfaces from the vapor resulting from the intense pulsed heat loads.

Important questions related to dust in fusion devices that come in mind are:

1. dust formation mechanisms, its identification and quantification of dust-formation rate;
2. properties and its characterization;
3. interaction of dust interaction with the fusion plasma, its assessment and characterization;
4. analytical study of the consequences.

This chapter will address some aspects of these questions in its following sections.

3.2 PROCESS OF EROSION-REDEPOSITION IN TOKAMAK

The inside of the vacuum-vessel of a magnetic-confinement fusion device is complex. It contains plasma-heating structures, & on the vessel top protection limiters in poloidal-planes, & a divertor at the bottom. The size of the magnetically-confined hot plasma is defined by limiters and divertors which handle most of the heat & outflow of the particles of the plasma. The area of the wall which is further away from the confined plasma suffers particle exposure and a less intense heat.

In majority of the large fusion devices presently used, significant parts of the exposed plasma surfaces are covered with composites of carbon or graphite. Because of their good thermomechanical properties & because of the low atomic number Z of carbon makes it less important as a contaminant in plasma than the materials with high Z. These materials are preferred for components of high heat flux.[6] Carbon is generally considered a material choice for ITER. Carbon due to a high physical sputtering yield suffers from large erosion rates and additional chemical erosion. As a consequence of ionic and atomic H_2 exposure from the fusion plasma, hydrocarbons are formed and from the surfaces they are released into the plasma edge where they dissociate & ionize [7].

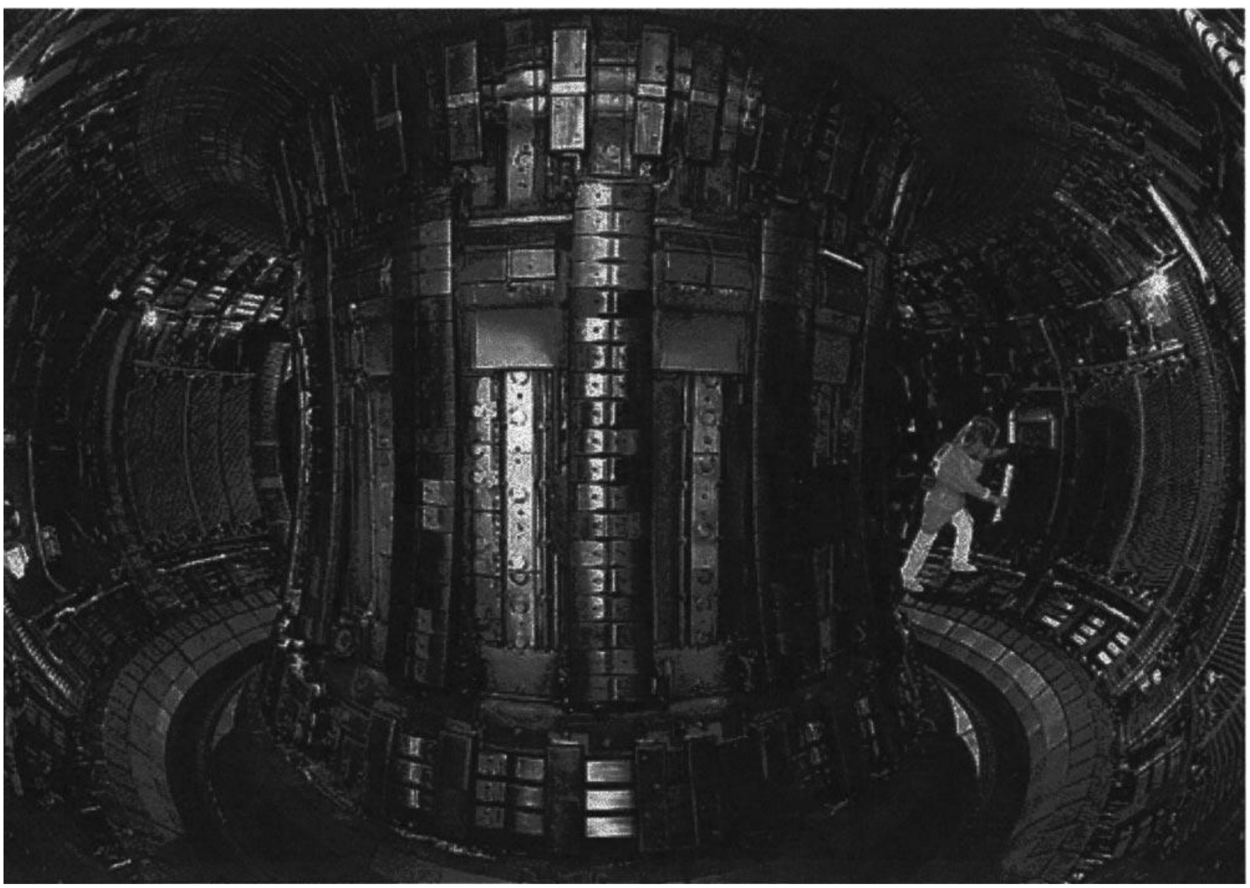

Fig.3.1 Inside view of vacuum vessel of Joint European Torus [26]

By thermally overloading the components, sublimation of carbon may occur. Edge Localized Modes (ELM's) are critical in this respect, instabilities driven by the pressure gradient at the plasma edge, periodically exposing divertor plates to high power fluxes. In the case of the largest existing tokamak, JET [8], the power of the ELM was found near to a few GWm^{-2} occurring at a rate of 100Hz during 100ms [9]. Perturbations led to even higher heat-fluxes.

Disruptions are the rapid uncontrolled quenching of the discharge during which the whole stored plasma energy is dumped on part of the surface in a very short time. In ITER the thermal load from a disruption is estimated to be 100 GWm^{-2} during 1 ms. The material can respond to this thermal load only by sublimation. The localized power loading may create a high vapor density in front of the affected surface.

Magnetic-confinement of fusion-device which is essentially a closed system for condensable materials, at the end of a plasma pulse only volatile gases leave through the vacuum pumps. For example, in the TEXTOR tokamak [10], the average flux of H (D) at the leading edge of the poloidal graphite limiter comes out to be $10^{23}m^{-2}s^{-1}$. The averaged erosion yield comes out to be 2 x 10^{-2} which results in a primary loss rate of 2 x $10^{21}m^{-2}$ s carbon atoms. Because of regular plasma exposure it results to a gross erosion of 1 m/year at the limiter tip.

Eroded material, practically all, is redeposited reducing significantly gross erosion but unfortunately redeposition of material does not completely occur at its point of origin, infact some part is gradually transported from the high heat-flux regions (erosion dominated) to the low heat flux regions (deposition dominated) in repetitive erosion-deposition processes. Carbon layers usually grow in the low heat flux regions where these layers retain hydrogen. Concentration of hydrogen isotope depends on the kinetic-energy (K.E) of the impinging plasma species & on the temperature history of the respective area. The mechanical strength of the layers are very poor and easily fall off the surface. 50% of the retained hydrogen will be tritium, in the case of future fusion devices. This radioactive dust continues to increase the beta-decay of the tritium(T) could lead to nuclear-induced plasma which could influence the initiation stage of a thermonuclear plasma.

3.3 MECHANSM OF DUST FORMATION IN TOKAMAK

In the framework of a study for ITER effective surface area, the size distribution, & the total amount of dust from the big tokamaks like TFTR (Tokamak Fusion Test Reactor), Doublett-3-D, 13 and JET (Joint European Torus) was analyzed. A log-normal size distribution has been found which spans a range from several 10nm up to the mm range. In the case of the Doublet-3-D tokamak, the concentration of mass was found to be in the range from 10–100μg on the floor and lower horizontal surfaces and 0.1-1μgcm^{-2} on vertical surfaces. For an integrated plasma exposure time of less than a few hours, the total amount is estimated to be between 30–120g [11]. Depending on the assumptions at the operation scenario, estimates for ITER are in the range of few kg to 10 kg. Usually the dust-composition is dominated by carbon but it may also include other materials used inside the tokamak or those for conditioning the wall.

On inspecting dust from TEXTOR using SEM shows that the majority of particles are flakes of smaller fragments of redeposited layers.[3] Fig.3.2 shows the blistered columnar structure which can be seen from a SEM and picture of a large flake from a deposition dominated area or low heat flux regions of the TEXTOR limiter. The majority of flakes found at the bottom of TEXTOR are similar to that shown in Fig.3.2. Thus, the increase in the plasma fluence increased the redeposition & thus dust formation by spalled. This mechanism in long pulse devices must be considered carefully. About 15% of the dust in the case of TEXTOR was found to be ferromagnetic [3].

Metal atoms are enriched in the flakes due to preferential re-erosion of the pure carbonaceous matrix. Magnetic particles will interact with magnetic fields and their gradients.

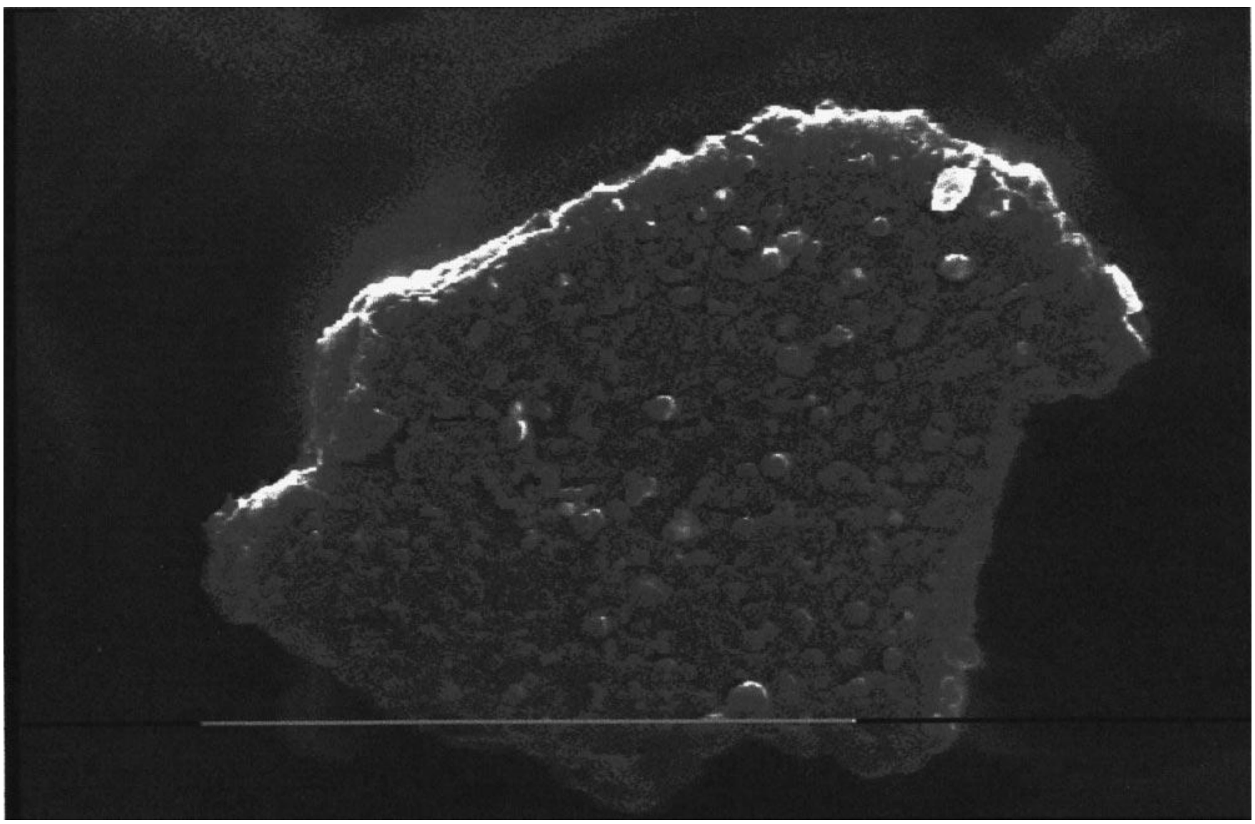

Fig.3.2 Redeposited large flake from a TEXTOR limiter [27]

By spalling thin-films deposited for the purpose of conditioning the wall, flakes of typically a few hundred nm thickness may be liberated [6]. The thin-films may flake when exposed to damp air during an opening but usually they have an excellent adhesion. Further plasma operation lead to plasma-surface interactions which may then liberate flakes.

Significant number of nearly perfect metallic-spheres with radii varying from 0.000005-0.0005mm were identified in TEXTOR. Most probably, coagulation of metal atoms lead to the formation metal-spheres on hot graphite surfaces. Initially due to unipolar arcing they are evaporated from metal wall elements, then via the plasma they are transported to the limiter surface made of graphite. Metals cannot wet graphite.

When the limiter gets hot from the thermal load of the plasma, the surface mobility of the metal atoms increases, then the atoms clot and form little metallic spheres. Then they are released by plasma–surface interactions from the limiter. Mostly during start-up phase of plasma or at disruptions of plasma, arcing occurs. During these phases electric fields are strongest leading to a breakdown of plasma sheath locally. Another possible mechanism for formation of the metal spheres during arcing can be the coagulation of particles from oversaturated vapor phase.

The failure mode of carbon material for repeated exposure to low powers is a loosening of the material structure by propagating cracks initiated by large stress and strain. Finally the ejection of grains may occur. In the dust collected from TEXTOR graphite grains were easily distinguished from flakes by their facetted appearance. They have an average diameter of typically 5–20 mm. For higher power fluxes (ELMs, disruptions) the evaporation or sublimation of material is dominant. The vapor has a high density close to the surface and the particles have a short mean free path. Coagulation processes from supersaturated vapor leads to the formation of small particles of average radius of several 5–50nm due to coagulation processes. This dust formation mechanism was readily verified in a lab experiment where different carbon materials were repeatedly exposed to 0.5–1.5GWm^{-2} power loads using an electron gun of high power [16-18].

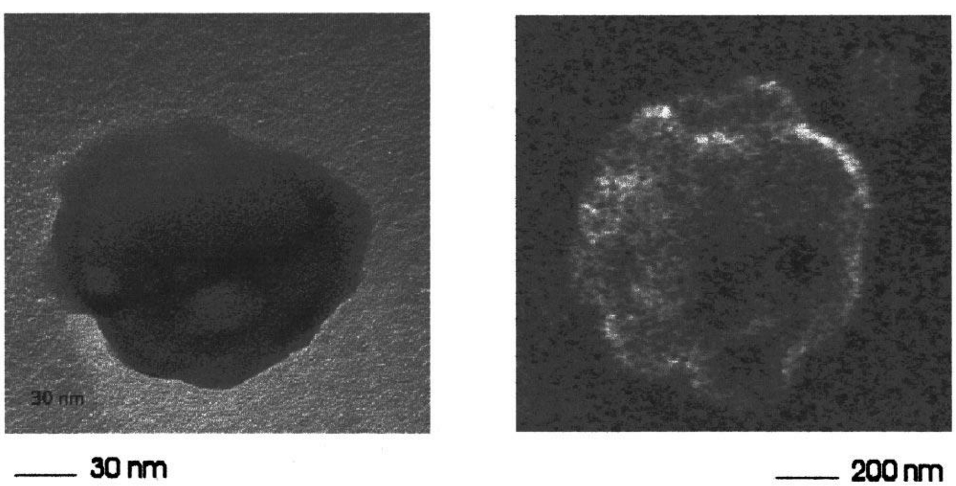

FIG.3.3 Left: TEM of a globular C-particle which was formed by coagulation from dense carbon vapor. Right: Coagulated dust particle in TEXTOR. [28]

TEM (Transmission electron microscopy) of the released material shows small globular clusters (see Fig. 3.3, left-hand side), and also evidence for the formation of fullerene-like materials.

Interestingly, a similar type of particles was identified in the TEXTOR dust (Fig. 3.3, right-hand side) consisting of agglomerates of individual single globular particles of about 100 nm diameter. They may have been formed by coagulation from C vapor during arcing, ELMs or disruptions. Another possible mechanism is the growth of dust in the scrape off layer [2,3] This mechanism would be particularly important in future long-pulse devices. The growth will probably occur via negative hydrocarbon ions and multiple ion–neutral reactions. In detached plasmas the convected power to the limiter or divertor is small but the isotropically radiated power fraction is high. The conditions are close to those of a process plasma. A detached limiter plasma in TEXTOR has typically $n_e \approx 10^{17} m^{-3}$, $Te<5eV$, a significant fraction of neutral atoms and molecules and a concentration of hydrocarbons and CO near the wall of 10% or more [19]. Dust formation has been observed under such conditions in reactive process plasmas [20,21]. Once negative ions are formed by electron attachment, they are well confined in the edge plasma. The sheath potential in front of the limiter surfaces repels them and prevents them from reaching the material surface. The magnetic field confines them in the radial direction. A friction force from the background plasma is acting on these particles, driving them away from the stagnation point. Thus probable locations of dust particles will be close to wall protrusions where an effective trap from the superposition of these forces exists, see Fig. 5. It is interesting to note that C1 , *C*2 ,...,*Cn* clusters and several C*x*H*y* radicals exhibit a high electronegativity (CH_2=3.39 eV, C_2H=2.94 eV) making their negative ions rather stable. Similar conditions also exist for detached divertor conditions, with higher absolute densities, however.

3.4 CHARGING OF DUST BY DECAY MECHANISM

A carbon particle of thickness 1mm with radius of 2.5 mm is considered with a total H-isotopes concentration of 0.4 per carbon atom of which half is tritium is considered in the following rough estimate. In tokamak the mean density of carbon film which are redeposited has been calculated to $1.5 gcm^{-3}$[12]. With respect to b-decay tritium is unstable which has a maximum electron energy of 18600eV and a half-life 1/2512 years. It is assumed that all electrons leave the particle into the vacuum. The steady state positive charge on the particle depends on the effective neutralization rate. If we assume for the tritiated carbonaceous dust a secondary electron emission yield of unity and in the evacuated torus a mean charge lifetime of 1 s an equilibrium charge of $Q=5x10^2$ elementary charges accumulates. The particle would levitate at an electric field strength $E=38Vcm^{-1}$.

3.5 POSSIBLE DUST IMPACT ON PERFORMANCE OF PLASMA

Disruptions can be induced if large-particles fall into a fusion plasma. Narihara *et al.* [22] used the Thomson scattering set up in JIPPT-2U (Japanese Institute of Plasma Physics Tokamak-2 Upgrade) to study the influence of small carbon particles with radius 1 mm on the performance of tokamak discharges. Dust was dropped from the top of the machine and the authors concluded that an amount of about 10^6 particles of 2 mm do not affect a fully developed discharge but if particles exist in the main volume before start up of the plasma increased impurity concentrationsare observed.

At the end of discharge of fusion plasma discharge, most particles fall at the floor of the device A significant reservoir may get accumulated after some period of time. Light particles may be reinjected into the fusion plasma by magnetic and also by electric forces when dust flakes are charged by plasma contact. They may then be levitated close to the wall.3,23,24 Magnetic particles experience a magnetic-force and may be sucked into the main vessel volume when the toroidal magnetic field is switched on. Plasma breakdown and burn through may be seriously impeded under these conditions. During the start-up phase of tokamak plasma, the intense impurity radiation observed often may be due to levitated dust.

By the measurement of the line radiation of ions or neutral atoms, erosion rates of components of wall can be determined. By conglomeration of cluster formation, impure molecules or atoms will be consumed before they can radiate, hence eluding emission spectroscopy. Fine particles may be carried to far away places from their point of origin which are subject to thermal forces, unlike splashes of massive melted metal, which are usually deposited in the vicinity.

Dust particles act as a sink for electrons. The dust grain charge is about 10000 elementary charges for a 0.5mm radius particle per eV electron-temperature which increase with the size of particle & temperature of electron. The dynamic response of the plasma-edge, example, to low frequency acoustic waves can be altered by heavy negative charged particles.

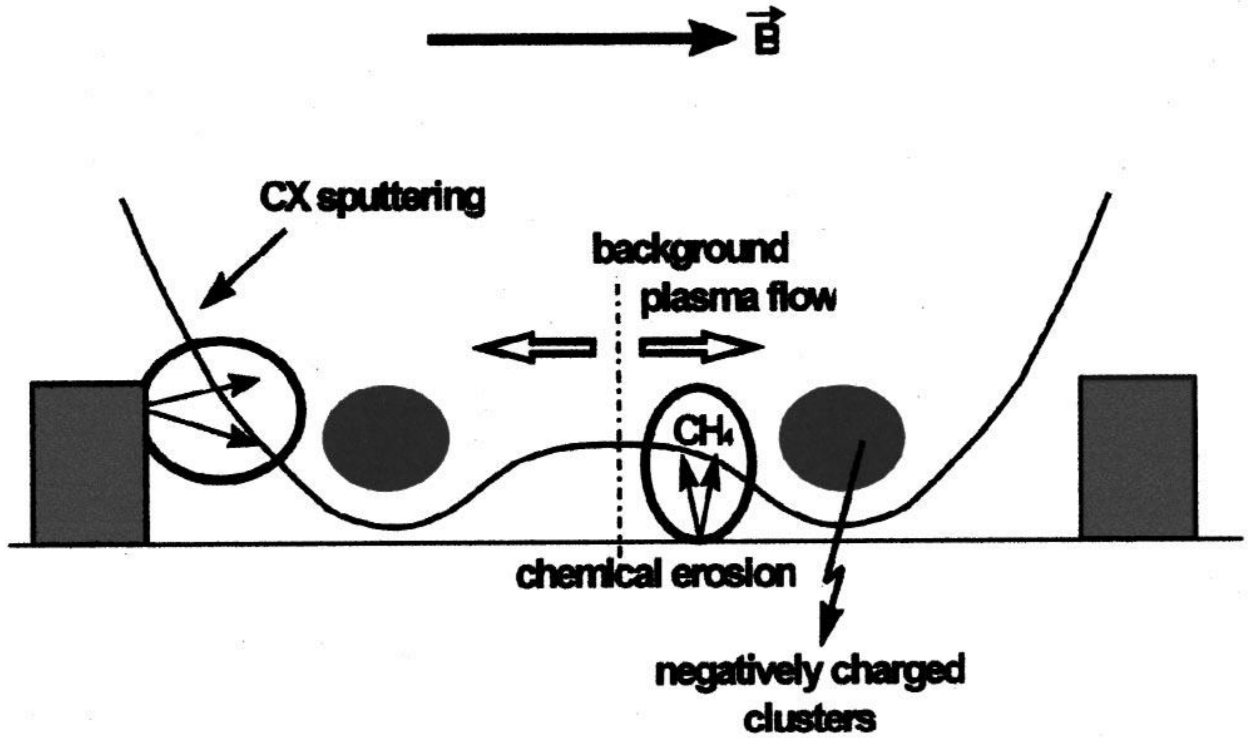

Fig.3.4 Schematic diagram of effective-potential for negative-cluster in the plasma-edge of a tokamak between limiters [29].

Decay of tritium through radioactivity may lead to complex effects additionally. During breakdown and initial current ramp phase of a fusion plasma rapidly varying eddy currents are flowing in the vessel. Due to this variation they cause to levitate the charged dust particles, the electric-field strength need to be large enough as in this case. Burn-through of the plasma becomes difficult if such particles get before a significant amount of current is established. The dust particles would be vapourized, carbon atoms which are partially ionized radiate power out of plasma & make a significant contribution to resistivity of plasma. For plasma startup, devices with superconducting coils particularly low loop voltages (of the order of 0.001kV) are required for technical reasons. The presence of dust is critical in this case.

For plasma breakdown to occur, the pressure of gas in the vessel is increased to about 0.001 mbar, the fast electrons will ionize the gas along their track from the tritium decay. At this pressure, the electrons range is of the order of $10x10^2$m. Because of toroidal-magnetic field of the order of 5T, the electrons have very small gyro-radii compared to the vessel dimension and they may efficiently ionize the gas. Assuming a mean value of 0.035keV/electron-ion pair & full stopping of the fast electrons about 500electron-ion pairs are emitted. It is assumed that the inner surface of the tokamak (of the order of $1000m^2$) is covered with half of dust and films redeposited as discussed above.

Under the assumption that half of the b’s out of an escape depth of 1 mm leave the film towards the main vessel volume, a total flux of about total flux of 1.23 ions & electrons per second. Assuming electrons confinement-time of 0.5s & consisting volume of the vessel volume as $1000m^3$ results into electron-density of the order of $5x10^9cm^{-3}$ from this nuclear induced plasma. In a recent paper by Fortov, Nefedov, and Vladimirov has shown that radioactive particles induced plasma is established in a simple configuration of parallel-plate even when no super-imposed magnetic-field is present. Formation of ordered dust-structures & even the levitation of dust has been observed. Hence, it appears crucial to consider charging of dust by nuclear-induced plasma and nuclear-decay.

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CHAPTER 4

MATHEMATICAL MODELING

4.1 INTRODUCTION

Dust in plasma are partially or fully ionized gas at low temperature which comprises of ions, electrons, neutral molecules & extremely heavy electrically charged dust grains. The presence of dust in plasma can considerably change its properties is well established fact. Charging process of dust introduces new realm in Physics by altering the properties of dielectric of plasma. With frequencies to the tune of dust charge frequency, the most affected part of plasma are plasma modes. On instability analysis of growth rate it is found that it is dependent on dust parameters. In real situation, however, size distribution is exhibited by dust grains. Dust grain particles are responsible for the occurrence of new phenomena and introducing new plasma equilibrium. To study the various properties of the dusty plasma, researchers around the world have been showing a great deal of interest. Fluctuation of dust charge may occur due to several reasons. Many researchers have tried incorporating the effect of fluctuating charge on wave propagation and have found several interesting result [1]. Cui and Goree [2] have developed a simulation code to for charge fluctuation characterization. A discrete charging model was used where dust grain charge is fluctuating because of the random absorption of electrons and ions at the surface of grain. D'Angelo [3] has examined the Rayleigh-Taylor instablity in a dust plasma & found that presence of dust which are negatively charged decreased the range of unstable wavenumbers. Tsytovich and Havnes [4] has considered a novel kinetic effect which is arising from the inhomogeneities occuring in dust charges and demonstrated collisionless drift wave instability. Mahant et al [5] had shown that the fluctuations in dust-charge leads to dampening of lower-hybrid wave in cool dusty-plasma. Islam et al [6] have found that the sum of the dust charge fluctuation effect and Landau damping leads to damping of lower-hybrid mode in a magnetized dusty-plasma. Prakash et al [7] have investigated the electron beam driven lower-hybrid wave in case of a magnetized dusty plasma where as Kuley and Tripathi have worked on lower hybrid instability in a tokamak under neutral beam injection and magnetic shear but in the absence of dust.

In this project we consider lower hybrid waves in dusty, homogeneous-plasma plunged in a uniform and static magnetic field. Effects of dust charge fluctuations, temperature of plasma electrons, dust grain size, number density of dust grains, and beam velocity on LHW are studied using fluid theory.

In section 4.2, we present the instability analysis and derives dispersion relation of lower hybrid wave in presence of fluctuating dust charges. The instability growth rate has been obtained here using 1^{st} -order perturbaton techniques.

Chapter 5 gives a brief discussion of results on the excitation of LHW instability in presence of fluctuating dust charges by neutral beam.

4.2 INSTABILITY ANALYSIS

A mathematical model has been developed to study the excitation of lower hybrid instability triggered by the injection of a transverse neutral beam in a tokamak with magnetic shear. Dust is also introduced in the plasma to study its effect on the growth rate.

We model the tokamak by a plasma slab with uniform electron density n_o placed in a sheared magnetic field $B = B_0[\hat{z} + (\alpha x / a_1)\hat{y}]$, where a_1 is the plasma minor radius and $\propto$ is the magnetic shear parameter. The x, y, and z directions in the slab geometry corresponds to radial, poloidal & toroidal directions in the tokamak configuration. A neutral beam with velocity $v_{ob}\hat{y}$, density n_{ob} propagates through the plasma. This beam quickly turns into an ion beam of charge e and mass m_b. We perturb the equilibrium by lower hybrid wave perturbation of electrostatic potential which is given by :-

$$\phi = \phi_o(x)e^{-i(\omega t - k_y y - k_z z)} \tag{1}$$

where ω lies in the range –

$$\omega_{ci} << \omega << \omega_{ce} \text{ and } K_\perp \rho << 1$$

ω_{ci} and ω_{ce} are the ion and electron cyclotron frequencies and ρ is the electron larmor radius. In this limit the ion motion can be taken to be unmagnetized and we can employ the fluid equation for electron response.

Equation of motion-

$$m\,[\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\nabla)\vec{v}] = -e\vec{E} - e\vec{v} \times \vec{B} \tag{2}$$

We know that-

$$\boldsymbol{E} = -\nabla\phi$$

On linearization Eq. (2), we get

$$m\,[\frac{\partial \vec{v_1}}{\partial t} + (\vec{v_1}.\nabla)\vec{v_1}] = e\,\nabla\phi - e\,\vec{v} \times \vec{B} \tag{3}$$

Velocity v will have two components –

$$\vec{v_1} = \vec{v_1}_\perp + \vec{v_1}_{||}$$

On linearization Eq. (3), we get

$$v_{1\perp} = \frac{e}{m} \frac{\nabla_{\perp}\phi \times \omega'_{ce} + i\omega\nabla_{\perp}\phi}{\omega^2 - \omega'^2_{ce}} \tag{4}$$

$$v_{1\|} = -\frac{e}{mi\omega}\nabla_{\|}\phi,$$

where $\omega'_{ce} = \omega_{ce}[\hat{z} + (\alpha x / a_1)\hat{y}]$, $\vec{\omega}_{ce} = \frac{e\overrightarrow{B_0}\hat{z}}{m}$, $\frac{\partial}{\partial t} = -i\omega,$

and $\nabla\phi = \nabla_{\perp} + \frac{1}{B(B.\nabla)}$

Using $\perp_r$ *and* $\|_r$ components of velocity in the equation of continuity –

$$\frac{\partial n}{\partial t} + \nabla.(n_o \vec{v}) = 0 \tag{5}$$

We get perturbed electron density as :-

$$n_{1e} = \frac{n_0 \nabla v_1}{\omega}$$

$$= \frac{n_0 e}{m}\left[\frac{\nabla_{\|}^{\ 2}}{\omega^2} + \frac{\nabla_{\perp}^{\ 2}}{\omega^2 - \omega'_{ce}{}^2}\right]\phi$$

$$= \frac{n_0 e}{m}\left[\frac{\nabla_{\|}^{\ 2}\phi}{\omega^2} - \frac{\nabla_{\perp}^{\ 2}\phi}{\omega'_{ce}{}^2}\right] \tag{6}$$

As $\omega^2 << \omega^2{}_{ce}$

For ions, we will neglect $\vec{v} \times \vec{B}$

∴ for ion response, the perturbed ion density come out to be-

$$n_{1i} = -\frac{n_{0i}e}{m_i\omega^2}\nabla^2\phi \tag{7}$$

Again, the ion beam response is assumed to be un-magnetized,

The equation of motion for ion :-

$$m_i\ [\frac{\partial\vec{v}}{\partial t}+(\vec{v}.\nabla)\vec{v}]=e\vec{E} \tag{8}$$

We know that-

$$\boldsymbol{E}=-\nabla\phi$$

$$m_i\ [\frac{\partial\vec{v}}{\partial t}+(\vec{v}.\nabla)\vec{v}]=-e\nabla\phi$$

$$m_i\vec{v}\ [-i\omega+ik_y v_{ob}]=-e\nabla\phi$$

Let $m_i = m_b$, then

$$\vec{v}_{1b}=\frac{-e\nabla\phi}{m_b[-i\omega+ik_y v_{ob}]}$$

$$\vec{v}_{1b}=\frac{e\nabla\phi}{m_b(\omega-k_y v_{ob})} \tag{9}$$

Now, equation of continuity,

$$\frac{\partial n}{\partial t}+\nabla.(n_o\vec{v})=0$$

On linearization the above equation, we get

$$\frac{\partial n_{1b}}{\partial t}+\nabla.\left(n_{1b}\vec{v}_{0b}+n_{0b}\vec{v}_{1b}\right)=0$$

$$-i\omega n_{1b}+n_{1b}\left(\nabla.\vec{v}_{0b}\right)+\nabla n_{0b}\vec{v}_{1b}=0$$

Putting the value of $\vec{v}_{1b}$, we get perturbed beam density

$$-i(\omega-k_y v_{0b})n_{1b}=\nabla n_{0b}\times\frac{e\nabla\phi}{im_b(\omega-k_y v_{0b})}$$

$$n_{1b}=\frac{n_{0b}e\nabla^2\phi}{i^2 m_b(\omega-k_y v_{0b})^2}$$

$$n_{1b}=-\frac{n_{0b}e\nabla^2\phi}{m_b(\omega-k_y v_{0b})^2} \tag{10}$$

$$n_{1d} = -\frac{n_{0d} Q_{od} \nabla^2 \phi}{m_d \omega^2} \qquad (11)$$

From Jana et al, perturbed dust grain charge is given by

$$Q_{1d} = \frac{i\,|\,I_{oe}\,|}{\omega + i\eta}\left(\frac{n_{1i}}{n_{0i}} - \frac{n_{1e}}{n_{0e}}\right) = \frac{i\,|\,I_{oe}\,|}{\omega + i\eta}\left[-\frac{e\nabla^2\phi}{m_i\omega^2} - \frac{1}{m}\left(\frac{\nabla_{\parallel}^2\phi}{\omega^2} - \frac{\nabla_{\perp}^2\phi}{\omega'^2_{ce}}\right)\right]$$

Using Poisson's equation, we get

$$\nabla^2\phi = (4\pi e n_{1e} - 4\pi e n_{1i} - 4\pi e n_{1b} - 4\pi Q_{od} n_{1d} - 4\pi e n_{od} Q_{1d})\phi$$

$$\nabla^2\phi = \frac{\omega_p^2}{\omega^2}\nabla_{\parallel}^2\phi - \frac{\omega_p^2}{\omega'^2_{ce}}\nabla_{\perp}^2\phi + \frac{\omega_{pi}^2}{\omega^2}\nabla_{\parallel}^2\phi + \frac{\omega_{pi}^2}{\omega^2}\nabla_{\perp}^2\phi + \frac{\omega_{pd}^2}{\omega^2}\nabla_{\perp}^2\phi + \frac{\omega_{pd}^2}{\omega^2}\nabla_{\parallel}^2\phi + \frac{\omega_{pb}^2}{\bar{\omega}^2}\nabla_{\perp}^2\phi + \frac{\omega_{pb}^2}{\bar{\omega}^2}\nabla_{\parallel}^2\phi$$
$$+\left(\frac{i\beta}{\omega + i\eta}\right)\left[\frac{\omega_{pi}^2}{\omega^2\delta}\nabla_{\parallel}^2\phi + \frac{\omega_{pi}^2}{\omega^2\delta}\nabla_{\perp}^2\phi + \frac{\omega_p^2}{\omega^2}\nabla_{\parallel}^2\phi - \frac{\omega_p^2}{\omega'^2_{ce}}\nabla_{\perp}^2\phi\right]$$

(12)

On solving and arranging for $\omega << \omega_{ce}$,we obtain

$$1 + \left(1 + \frac{i\beta}{\omega + i\eta}\right)\left(\frac{\omega_p^2 k_z^2}{\omega^2 k^2} - \frac{\omega_p^2 k_y^2}{\omega'^2_{ce} k^2}\right) - \left(1 + \frac{i\beta}{\delta(\omega + i\eta)}\right)\left(\frac{\omega_{pi}^2 k_y^2}{(\omega^2 - \omega'^2_{ce})k^2} + \frac{\omega_{pi}^2 k_z^2}{\omega^2 k^2}\right) - \frac{\omega_{pd}^2}{\omega^2}$$
$$= \frac{\omega_{pb}^2 k_y^2}{(\bar{\omega}^2 - \omega'^2_{ce})k^2} + \frac{\omega_{pb}^2 k_z^2}{\bar{\omega}^2 k^2}$$

(13)

where

$\sqrt{4\pi\frac{n_{0e}e^2}{m}} = \omega_p$, electron plasma frequency

$\sqrt{4\pi\frac{n_{0i}e^2}{m_i}} = \omega_{pi}$, ion plasma frequency

$\sqrt{4\pi\frac{n_{0b}e^2}{m_b}} = \omega_{pb}$, beam plasma frequency

$$\sqrt{4\pi \frac{n_{od} Q_{od}^2}{m_d}} = \omega_{pd}$$, dust plasma frequency

$\bar{\omega} = \omega - k_y v_{ob}$ and $\beta = 0.397\omega_{pi}^2 (1-1/\delta)(a/v_{te})(m_i/m_e)$ which is coupling parameter.

$v_{te} = \sqrt{\frac{2T_e}{m_e}}$ is the electron thermal velocity, a is dust grain size.

Eq. (13) can be rewritten as

$$(\omega^4 + B\omega^2 + C)(\omega + i\eta) + i(\beta_1 + \beta_2 + \beta_3)\omega^4 = \omega^2(\omega^2 - \omega'^{\,2}_{ce})(\omega + i\eta)\frac{\frac{\omega_{pb}^2 k_y^2}{(\bar{\omega}^2 - \omega'^{\,2}_{ce})k^2} + \frac{\omega_{pb}^2 k_z^2}{\bar{\omega}^2 k^2}}{K} \tag{14}$$

where

$$K = 1 + \frac{\omega_p^2 k_y^2}{\omega'^2_{ce} k^2}$$

$$B = -\left[\omega'^2_{ci} + \frac{1}{K}\left(\omega_p^2 k_z^2 / k^2 + \omega_{pi}^2 + \omega_{pd}^2\right)\right]$$

$$C = \frac{\omega_{ci}^2}{K}\left(\omega_p^2 k_z^2 / k^2 + \omega_{pi}^2 k_z^2 / k^2 + \omega_{pd}^2\right)$$

$$\beta_1 = \frac{\beta}{K}\left(\frac{\omega_p^2 k_y^2}{\omega'^2_{ce} k^2}\right) \simeq \beta$$

$$\beta_2 = -\frac{\beta}{K\omega^2}\left(\frac{\omega_p^2 \omega_{ci}^2 k_y^2}{\omega'^2_{ce} k^2} + \frac{\omega_p^2 k_z^2}{k^2} + \frac{\omega_{pi}^2}{\delta}\right)$$

$$\beta_3 = \frac{\beta}{K\omega^4}\left(\frac{\omega_p^2 \omega_{ci}^2 k_z^2}{k^2} + \frac{\omega_{pi}^2 \omega_{ci}^2 k_z^2}{\delta k^2}\right)$$

Thus, we obtain the dispersion relation as

$$
\begin{aligned}
&(\omega^2-\omega_l^2)(\omega^2-\omega_n^2)[\omega+i(\eta+\beta_1+\beta_2+\beta_3)] \\
&= i(\beta_1+\beta_2+\beta_3)(\omega_l^2\omega^2+\omega_n^2\omega^2-\omega_l^2\omega_n^2)-\frac{\omega^2\omega_{pb}^2}{K}(\omega^2-\omega_{ci}^2)\left[\frac{k_y^2}{k^2(\bar{\omega}^2-\omega'^2_{ce})}+\frac{k_z^2}{k^2\bar{\omega}^2}\right]
\end{aligned}
\qquad (15)
$$

In the limit of vanishing beam density, Eq. (14) yields two roots (where $\eta,\beta_1,\beta_2,\beta_3$ are very small and thus can be neglected).

$$\omega_l = \omega_{lh}\sqrt{1+\frac{k_z^2 m_i}{k^2 m_e\delta}+\frac{\omega_{pd}^2}{\omega_{pi}^2}} \qquad (16)$$

where

$$\omega_{pd} = \sqrt{4\pi\frac{n_{od}Q_{od}^2}{m_d}}\ ,\ \omega_{lh} = \sqrt{\omega_{pi}^2\Big/\left(1+\frac{k_y^2\omega_p^2}{k^2\omega'^2_{ce}}\right)}$$

and $$\omega_n = \omega_{ci}\sqrt{\left(\frac{k_z^2 m_i}{k^2 m_e\delta}+\frac{\omega_{pd}^2}{\omega_{pi}^2}\right)\Big/\left(1+\frac{k_z^2 m_i}{k^2 m_e\delta}+\frac{\omega_{pd}^2}{\omega_{pi}^2}\right)} \qquad (17)$$

In our case, we are only considering lower hybrid mode which is obtained from equation (16). The instability of lower hybrid mode occurs at $\omega_l \approx k_y v_{ob}$ and maximum growth rate occurs at $\omega_l = k_y v_{ob}$ which is cerenkov interaction and $\omega_l \approx k_y v_{ob}$ is the resonance condition. Under this condition, a perturbative sol. of Eq. (15) (where $\beta_1,\beta_2,\beta_3,\eta$ are very small), we obtain the growth rate expression as:-

For $\omega_l \approx k_y v_{ob}$,

$\omega = \omega_l + \alpha_1 = k_y v_{ob} + \alpha_1$ where α_1 is a small frequency mismatch due to perturbation.

$\therefore \omega = k_y v_{ob} + \alpha_1$,

$\alpha_1 << \omega_l$

Now putting this value in our dispersion relation, we get

$$\alpha_1^3 = \frac{\omega_{pb}^2\omega_l\,(\omega_l^2 - \omega_{ci}^2)k_y^2}{2K(\omega_l^2 - \omega_n^2)k^2} e^{im2\pi}$$

$$\alpha_1 = \left(\frac{\omega_{pb}^2\omega_l\,(\omega_l^2 - \omega_{ci}^2)k_y^2}{2K(\omega_l^2 - \omega_n^2)k^2} \right)^{1/3} e^{im2\pi/3}$$

$$\therefore \alpha_1 = \left(\frac{\omega_{pb}^2\omega_l\,(\omega_l^2 - \omega_{ci}^2)k_y^2}{2K(\omega_l^2 - \omega_n^2)k^2} \right)^{1/3} (\cos m2\pi/3 + i\sin m2\pi/3)$$

where m = 0, 1, 2.

Now this 'm' can attain 3 values corresponding to 3 roots of α_1 . For m = 1, α_1 has positive imaginary part. Hence, growth rate γ is given as:-

$$\gamma = \mathrm{Im}(\alpha_1) = \left(\frac{\omega_{pb}^2\omega_l\,(\omega_l^2 - \omega_{ci}^2)k_y^2}{2K(\omega_l^2 - \omega_n^2)k^2} \right)^{1/3} \sin 2\pi/3 = \frac{\sqrt{3}}{2}\left(\frac{\omega_{pb}^2\omega_l\,(\omega_l^2 - \omega_{ci}^2)k_y^2}{2K(\omega_l^2 - \omega_n^2)k^2} \right)^{1/3} \quad (19)$$

Since, $\omega_{ci} << \omega$, hence our growth rate comes out to be

$$\gamma = \frac{\sqrt{3}}{2}\left(\frac{\omega_{pb}^2\omega_l}{2K}\frac{k_y^2}{k^2} \right)^{1/3}. \quad (20)$$

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CHAPTER 5

RESULT AND CONCLUSION

5.1 CALCULATION AND RESULTS

In our present calculation, we have used typical dusty plasma parameters which are:

electron plasma density, $n_{oe} = 10^9 – 2 \times 10^8$ cm^{-3}

ion plasma density, $n_{io} = 10^9$ cm^{-3}

ion beam density, $n_{ob} = 2.5 \times 10^8$ cm^{-3}

dust density, $n_{od} = 5 \times 10^4 – 8 \times 10^5$ cm^{-3}

guide magnetic field, $B_s = 320$ G

mass of ion, $m_i = 39 \times 1836 m_e$ (Potassium plasma)

mass of electron, $m_e = 9.1 \times 10^{-28}$ g

mass of dust, $m_d = 12 \times 1836 m_e$

dust grain size, $a = 10^{-4} – 4 \times 10^{-4}$ cm

$k_z / k \approx (m_e / m_i)^{1/2}$

We have assumed $Q_{od} = 2.88 \times 10^{-9}$ esu

beam velocity, $v_{ob} = 2 – 6 \times 10^8$ cm/s

temperature of electron, $T_e = 3$eV

temperature of ion, $T_i = 0.2$eV

charge on electron, $e = 4.8 \times 10^{-10}$ esu

speed of light, $c = 3 \times 10^{10}$ cm/s

The relative density of negatively charged dust grains, δ (= n_{oi}/n_{oe}) has been varied from 1 to 5.

Using above parameters, one can achieve the growth rate, γ.

After using these above parameters I used them for plotting several graphs of present results which could tell the behavior of the system when certain parameters are varied.

Case 1: γ as a function of δ (= n_{oi}/n_{oe}) with varying n_{oe}

In this case we have plotted the growth rate γ as a function of δ at different electron plasma density, n_{oe}. The values of n_{oe} has been varied from 10^9 – 2 x 10^8 cm^{-3}. We got the graph as shown below.

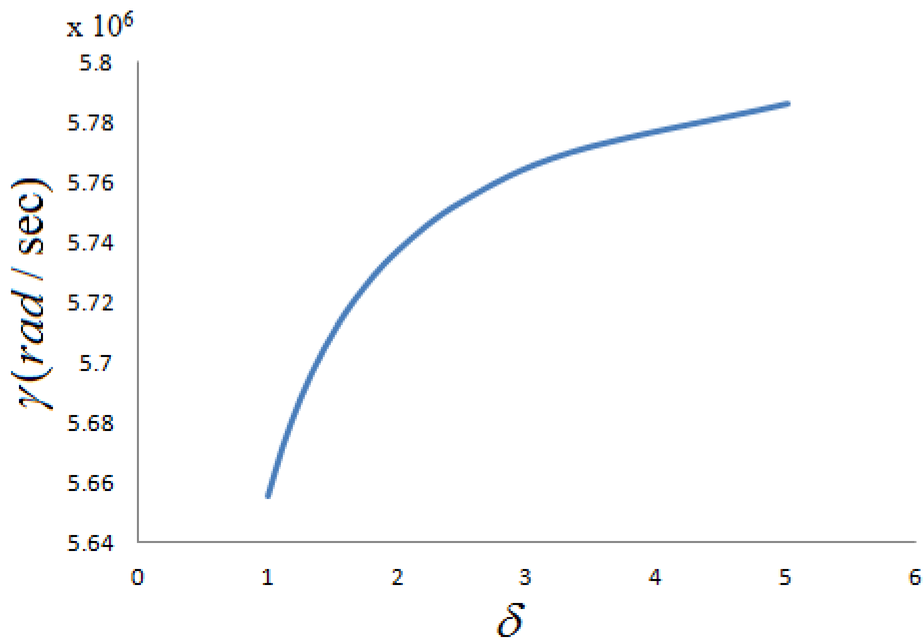

Fig.5.1 γ as a function of δ (= n_{oi}/n_{oe}) with varying n_{oe}

Case 2: γ as a function of δ (= n_{oi}/n_{oe}) with varying a

In this case we have plotted the growth rate γ as a function of 'δ' for different dust grain size, a. The values of dust grain size has been varied from 10^{-4} – 4 x 10^{-4} cm. The different values of 'a' taken are:

a = 10^{-4} cm, 2 x 10^{-4} cm, 4 x 10^{-4} cm

The graph that we plotted is shown below at these values.

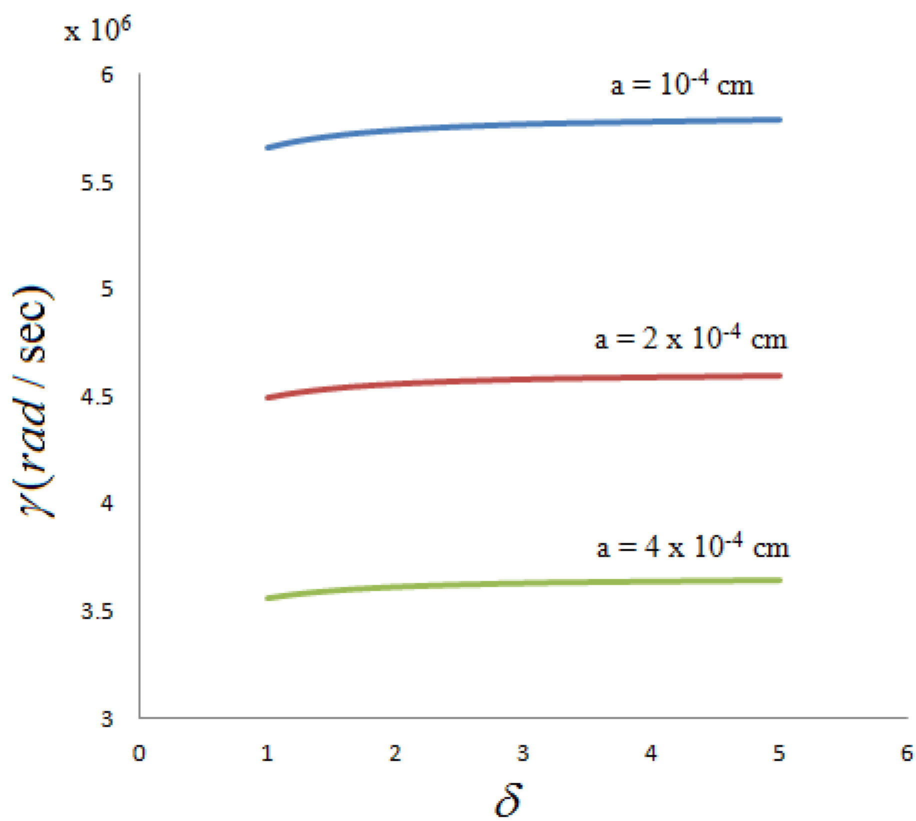

Fig.5.2 γ as a function of δ (= n_{oi}/n_{oe}) with varying a

Case 3: γ as a function of a

In this case we have plotted the growth rate γ as a function of dust grain size, a. The values of dust grain size ‘a’ has been varied from $10^{-4} - 9 \times 10^{-4}$ cm at δ=1. The graph is shown below.

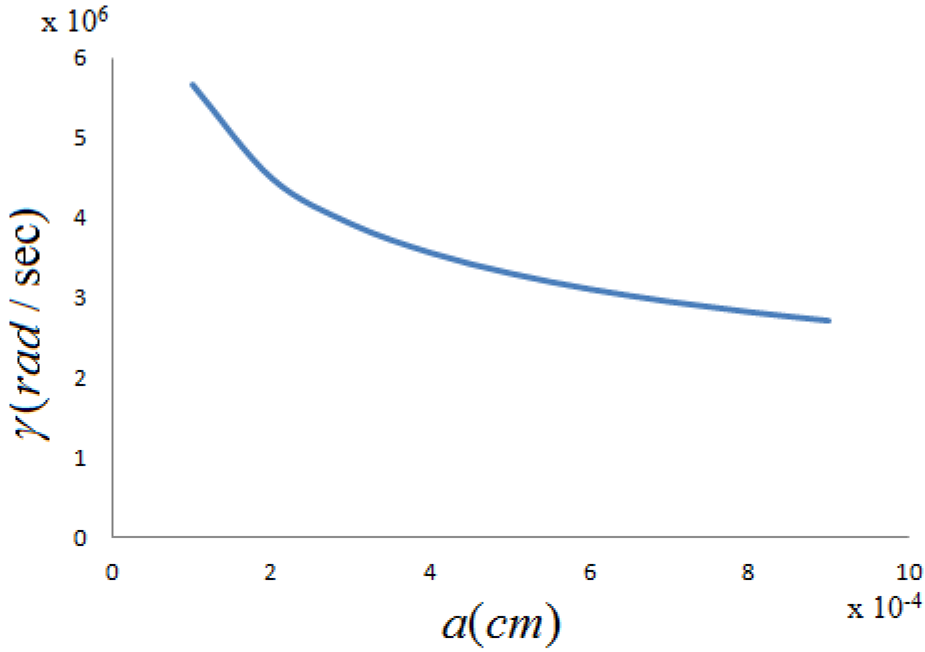

Fig.5.3 γ as a function of dust grain size, a

Case 4: γ as a function of δ with varying n_{od}

In this case we have plotted the growth rate γ as a function relative density of negatively, δ, with varying dust grain density, n_{od}. The values of dust grain density, n_{od} has been varied from 2 – 8 x 10^5 cm^{-3} at δ=5. The graph is shown below.

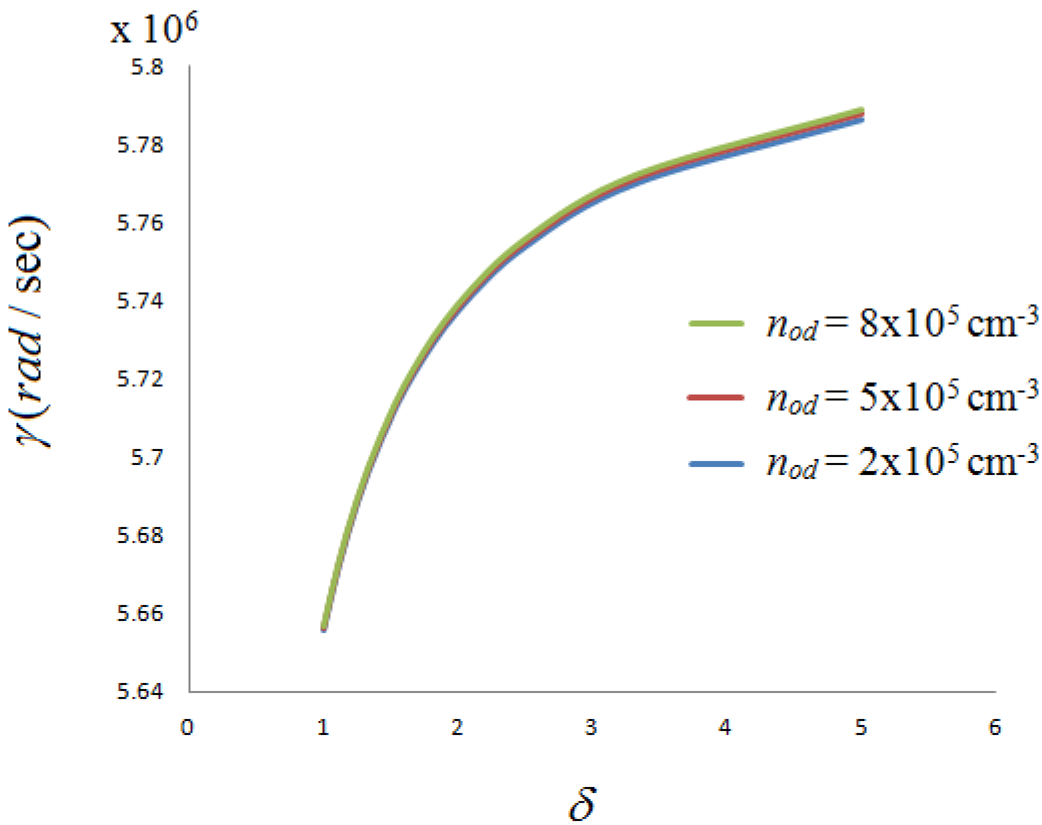

Fig.5.4 γ as a function of δ with varying n_{od}

Case 5: γ as a function of beam density n_{ob}

In this case we have plotted the growth rate γ as a function beam density, n_{ob}. The values of beam density, n_{ob} has been varied from 1 – 9 x 10^8 cm^{-3}. The graph is shown below.

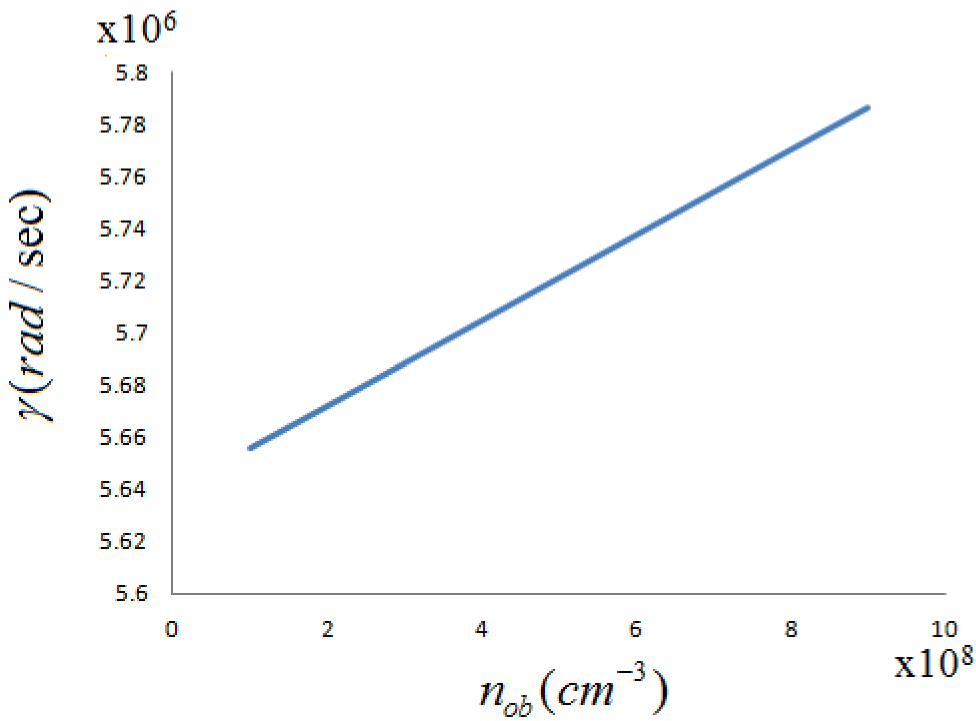

Fig.5.5 γ as a function of beam density n_{ob}

5.2 CONCLUSION

From the study of excitation of lower-hybrid wave instability by an ion beam, several important information can be derived from the graphs shown earlier.

In case 1, we can see that as the value of relative density of negatively charged dust grains, δ (= n_{oi}/n_{oe}) is increased, the growth rate γ also increases.

In case 2, we can see that as the dust grain size 'a' is increased the graph of γ as a function of δ shifts downwards, which means that the growth rate γ decreases as the dust size increases.

In case 3, we can see from the graph that as the dust grain size is increased, the growth rate falls down.

In case 4, we can see that the growth rate γ is dependent on dust density parameter. From the graph plotted at different δ values, as the dust density was increased our growth rate also increased.

In case 5, we can see that the growth rate γ is dependent on beam density parameter. As the beam density was increased our growth rate also increased.

Thus, from the above five cases we can conclude that the dust plays a significant role in the plasma-surface interactions in plasma processing of material experiments. Also, as the growth rate is proportional to magnetic shear. Hence, as we increase the value of magnetic shear, the growth rate will also increase which is in accordance with the findings of Kuley and Tripathi [1] though this has not been shown graphically here but can be easily deduced by looking at our expression for growth rate.

The dust particles charging model used here is valid only for conducting dust particles such as magnetite or graphite, found in terrestrial aerosols, interstellar clouds and laboratory plasmas or tokamaks. The presence of ion beam excites the lower hybrid mode, whose growth rate depends significantly on the dust grain size, dust grain charge fluctuations and dust grain density [2,3,4].

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