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Plasma physics: A review and applications with special reference to inertial confinement fusion energy

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A brief description of plasma, its types and fundamental requirements necessary to study the physics of plasma has been presented through this article. Information given here would be useful to those who have the basic knowledge of physics. Mathematical complications have been avoided to suit the purpose. Varied applications of plasma have been introduced. A little detail has been devoted to one of the major applications of plasma physics known as theoretical thermonuclear fusion studies. Physics of inertial confinement together with the role of self-generated magnetic field in the design of fusion targets have also been described.

Introduction

The term plasma was first introduced by two Americans, Langmuir and Tonks in 1923. It is natural to ask a question: what is plasma? The first answer may be ***the fourth state of matter*** whereas solid, liquid and gas are three commonly known states of matter.

Plasma is an ionized state of matter. It may be in the solid, liquid or gaseous form. Gaseous form of plasma is most widely studied. In contrast to an ordinary gas containing neutral molecules of atom, plasma contains mostly the charged particles and partly neutral particles. The charged particles are electrons and singly or multiply charged ions in such a number that make the plasma electrically neutral. Another basic difference between a neutral gas and plasma arises due to the entirely different character of the inter-particle interaction in them. In a neutral gas this force is of van der Waal's type, which is long range interaction and weak at large distances. As a result, each particle of the plasma can simultaneously interact in many ways with its innumerable immediate and distant neighbors. That is why plasma is rich with information but complex in character and so a rather hard nut to crack to understand its varied applications with proper theories associated with it. An ordinary gas is a good insulator at normal temperature and pressure. On the other hand with a sufficient degree of ionization and sufficiently high temperature plasma can become a conductor with high electrical conductivity. Because of the high conductivity, even a weak applied electric field can produce a large electric current. It is due to the fact that the electrons and ions in the plasma are completely free to move and hence can give rise to current. Electrons, due to their light mass are mobile in nature, and ions, being very heavy, are sluggish and mainly provide neutralizing background. Hence, electrons are main contributors to current in the plasma. The implication of large current in plasma due to mobile electrons is that in the external magnetic field plasma behaves like a diamagnetic substance (Chen 1974).

Regarding the average kinetic energy and temperature, particles (molecules or atoms) of gas have same kinetic energy and hence have the same temperature. But in the plasma, the average kinetic energies of the electrons, ion and neutral particles are generally different. Electrons have the highest average kinetic energy and neutral particles have least energy. The average kinetic energy of the ions lies between that of electrons and neutral particles. Hence, plasma is mixture of constituent particle at different temperatures at the same time.

Plasma strongly reacts with electromagnetic waves because it behaves like dielectric medium with a high dielectric constant. Electromagnetic waves below certain frequency, determined by the parameters of the particular plasma, cannot transmit through the plasma and are reflected back. Reception of radio signals throughout the earth stations may be example of an application based on the properties of ionospheric plasma. As a whole, plasma is a quasi-neutral system. It means that there cannot be significant excess positive or negative charge accumulated at any point in it. If there arise even slight deviation from charge neutrality, say one percent, it may give rise to very strong electric field. This strong field neutralizes the region of excess charge by transfer of electrons.

Thermodynamic equilibrium is attained through collisions in gases. Collisions among the molecules of a gas are like collisions between two billiard balls. Collisions in gas evolving more than two particles are extremely rare. In contrast, collisions between plasma particles are of an entirely different character.

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As mentioned already, the plasma particles interact with each other through long-range coulomb interaction, and a single electron can simultaneously interact with its innumerable neighbors, near and far. Hence, each particle of the plasma is always in the electric field produced by the rest of the electrons and ions. This electric field, again, is not static but changing incessantly in the magnitude and direction. However, on the averaging over a long time, the average field due to the random fluctuation will be zero, although this does not mean that average field is entirely zero always and everywhere. Thus, the internal micro-field inside the plasma, however small, constantly changes the magnitude and direction of velocity of charged particles. The intensity of the micro field being small on the average and of long range, the change in the direction of motion of the particles occurs continuously, not abruptly. So the role of the Coulomb force is dominant in plasma. For this reason it is also called ***coulomb gas.*** It is however, to be noted that the limit of the Coulomb force is not infinite. Polarization phenomenon shields it. The polarization occurring in the plasma limits the Coulomb force up to a certain length, known as the Debye length. This length is much smaller than dimension of the plasma but greater than inter particle spacing so that there are large number of particles within the sphere of radius equal to Debye length.

Because of the physical properties of plasma, a large number of applications related with its types have been devised in the laboratories in addition to natural ones. Examples of laboratory plasmas are plasma torch, arc, fluorescence etc. Commonly known three (solid, liquid and gas) states are only one percent or less in the scale of our universe. Some of the details on natural plasma have been discussed below.

Natural plasma

Plasma is the most natural state of matter. Most of matter (~99%) in the universe is in this state (Goswami 1995). Examples are sun, stars, nebulae, the Milky Way etc. Each of them is a vast plasma at very high temperature. Ionosphere, an important region of the atmosphere, is geophysical plasma and created due to photoionization when gases like N_2, O_2, CO_2, H_2O etc absorb solar radiation in daytime. The ionosphere is further divided into different layers designated by D, E, E_1, E_2, F_1, F_2 according to their height, electron number density, temperature etc. For example D layer has an average height of about 70 km and electron number density of about 10^{10} m^{-3}, while the F_2 layer has the corresponding values of 300 km and 10^{12} m^{-3}. Further in D region, density of neutral particles is so high that recombination processes are much affected there. In the E-layer several types of positive ions that have been observed are N_2^+, N^{++}, Al^{++}, etc. Metallic ions have been assumed to arise from burning of meteors and satellites etc. In the upper atmosphere of the Earth a few types of plasmas exists. One of them is airglow. There are two types of airglows, one observed at night and so called *night glow* and other observed during the day and called *day glow*. These are believed to originate from photoemission produced by various reactions. Likewise another spectacular glow known as the twilight glow is observed during sunset. Lighting, aurora, Van Allen radiation belt, solar wind, solar flare are other geophysical plasmas. There are two beautiful sceneries of aurora borealis and aurora australis in the upper atmosphere near the north and south pole regions. They occur due to deflection of charged particles ejected from the sun during magnetic storm from the equatorial to the Polar Regions in the earth's magnetic field. Similarly, Van Allen radiation belt is formed by electron and protons trapped by the Earth's magnetic field. Solar wind, solar flare, having all properties of usual plasma consist of charged particles. This wind compresses the Earth's magnetic field due to its pressure.

In the processes occurring in interstellar space plasma five kinds of molecules are involved such as CH, CH^+, CN, NaH and OH. First four molecules have been identified by optical spectra whereas the presence of OH molecules has been established through the experiments performed with radio waves. There are opinions in favor of the existence of polyatomic molecules as well but the fact has not been well accepted.

Application of plasma

There are many applications of plasma in our daily life. Plasma research varies from cheaper to very expensive ones. Thermonuclear fusion energy research is one of the most important and costly affair of plasma research. But every developed nation has been investigating on it because of its potential to meet global energy crisis of the future. It is because almost all resources on the Earth will be exhausted in a few decades when the rate of energy consumption will be more for vast population of the future.

Thermonuclear fusion

There are two schemes applied to harness nuclear energy: nuclear fusion and nuclear fission (Mukhin 1987). In the fission, heavy nuclei are broken into two nuclei having higher binding energy per nucleon, as the result there is release of energy. In fusion two light nuclei, such as deuterium-deuterium, deuterium-tritium, are combined together into a single nucleus having higher binding energy per nucleon. So there is also release of energy. A point to be noted here is that energy release per nucleon in fusion is greater than that released in fission. The energy release per nucleon in fusion of two nuclei ${}_1H^2$ and ${}_1H^3$ is about 6 MeV per nucleon whereas in fission it is about 0.8 MeV per nucleon. In addition nuclear fuel that is used in fission is isotope ${}_{92}U^{235}$ and in fusion the fuel is deuterium, ${}_1H^2$. In naturally occurring uranium there is only 0.7% of ${}_{92}U^{235}$ whereas ${}_1H^2$ are abundantly found in nature. Hence, fusion has merit over fission.

In the fusion, two interacting particles are brought sufficiently close to each other, about 2×10^{-15} m against coulomb repulsive force, so that they come in attractive nuclear field of each other. So, if there were no coulumbic repulsive force, it would have been very easy to fuse two nuclei. In order to overcome this difficulty, nuclei are heated in an excessively high temperature, about 100 million-degree. At such high temperature, interacting particles can no longer remain a neutral medium. It is converted into fully ionized plasma composed of electrons and nuclei. The random motion of nuclei would bring them within the range of nuclear force for fusion to occur. For this reason, fusion is also termed as thermonuclear reaction.

One more point to be noted here is about the confinement of fantastically hot fusion nuclei. Obviously, no material containers can be used for this purpose because they cannot exist in the solid state at such temperature. In addition since the heat conductivity of plasma is very high, thermal insulation is essential otherwise all the energy goes to the wall of the container and the desired high temperature cannot be reached. However, there is another possibility i.e. the use of specially shaped magnetic field called *magnetic bottles*, where fusing nuclei can be confined.

There are several magnetic confinement systems. These systems come in to sub-systems: open and closed systems. The open systems are Z-Pinch and θ-Pinch and mirror machine. The closed systems are Stellator, Tokamak and Levitron. Confinement time and number density of nuclei play the vital role in sustaining thermonuclear reaction. A condition, first given by J. D. Lawson, states that for the high probability of fusion, the product of confinement time and nuclear density of nuclei should be greater than or equal to 1.5×10^{22} m^{-3} sec. In the honor of its founder, the condition is called 'Lawson criterion'.

The other important possible application of plasma is the direct conversion of thermal energy into electric energy with the help of a magneto-hydrodynamic generator. In this case plasma jet is formed at first and then inserted perpendicular to magnetic field. Then an electromotive force will be induced in the plasma due to the interaction of the jet with the magnetic lines of force, which induces current. The current is made to pass through the load to obtain power.

In the reverse by applying large electric and magnetic cross-fields to the plasma one can obtain plasma beam with high velocity enough to act as an ordinary rocket propulsion system. In addition to the fusion reactor, MHD generator and plasma propulsion systems, there are a number of other plasma devices, which must be mentioned. The thermionic converter in which cesium plasma is used to produce high currents and significant portion of the thermal energy applied to the cathode is extracted as electric field. Plasma amplifiers, gas lasers, arc jets, fluorescent tubes are the additional plasma devices. Arc jets provide temperature as twice as of the hottest gas flames. So they can be used to melt metals like tungsten, carbon or molybdenum as well as for cutting or welding. Besides these, there are attention number of specialized tubes like the thyratron, grid-controlled thermionic arc-type rectifier and the ignitron that is used for switching.

Intertial confinement fusion

The possibility of heating of small volumes of dense hydrogen plasma by concentrating laser light up to the high temperatures at which thermonuclear reaction arise excited the scientists towards the inertial confinement fusion (ICF) (Duderstad and Moses 1982). The first demonstration of a man made inertial confinement fusion device came with the explosion by the United States of the first hydrogen bomb in 1952. In the intervening years a number of concepts were generated for laboratory inertial confinement devices using particle beams or intense laser pulses. In this high-density laser fusion the key idea is laser implosion of hydrogen isotope micro spheres to approximately 10^4 times liquid density in order to initiate efficient thermonuclear burning. Such fusion yields 50 to 100 times larger energy than the laser energy of 10^5 to 10^6 joules.

The laser fusion implosion system consists of a tiny spherical pellet of deuterium-tritium located in a large vacuum chamber, and a laser capable of generating an optimally shaped pulse of light energy. Laser irradiates this spherical target shell and delivers several megajoules of energy in a time of the order of 10 nanoseconds (Pokhrel 1983). At such high intensities, the irradiated areas of the target undergo rapid ionization initiating ablation (blow off) of its material in surrounding vacuum, which forms plasma with density below that of solid target. This plasma is called corona. The ablation generates enormous pressure or shock due to the rocket action, which implode the fuel (target) to density as high as 10^3 to 10^4 times that of solid density (Nuckolls *et al.* 1972). This compression would also raise the temperature of the fuel to fusion temperature, so that a thermonuclear burn is ignited. This burn would then propagate outward through the rest of the fuel pellet, igniting and burning it, to result in the explosive release of fusion energy. This scheme of fusion is called ***inertial confinement fusion***. The process of compression and thermonuclear ignition and burn would occur in a time much shorter than the time required for the pellet to blow apart (10^{-9}s). Hence, a premium is placed on developing driver beam capable of delivering large quantities of energy onto tiny targets (1 to 1000 mm in diameter) in a very short pulse (0.1 to 20 ns). It has to be noted that the blow off of plasma particles is not instantaneous process, but it takes certain time, because the inertia opposes such blowing apart. So one can take advantage of this fact and heat the fuel to thermonuclear temperature so fast that an appreciable number of fusion reactions occur before it is blown apart. It is the inertia that confines the fuel and for this reason the scheme is called inertial confinement fusion. Naturally, it requires an extremely large energy source to heat an appreciable mass of fuel to such high temperatures. In the corona, density of electron decreases away from pellet surface. So, as the laser penetrates the corona it encounters gradually increasing density and hence gradually gets absorbed more and more due to inverse bremsstrahlung. After penetrating certain depth it is completely absorbed and reflected back. At this stage, laser, being prevented from reaching the ablator by the coronal plasma, ceases its action of giving its energy directly to the ablator. The region where laser is completely absorbed is called critical surface and corresponding density is called critical density, n_c, which is given by $n_c = 10^{21}\lambda^{-2}$ where λ is wavelength of laser in μm. Since density is inversely proportional to square of wavelength, laser light of shorter wavelength is suitable for laser fusion. It is clear that critical surface shields the target from laser radiation. In such circumstances, the energy absorbed by inverse bremsstrahlung in the coronal plasma at densities equal to or less than the critical density is then conducted by electron to the cold ablation surface of solid target material (Nakarmi 1999).

In order to make ICF a success, it has been accepted that the morphology and magnitude of self-generated high order magnetic field be mapped and thus be taken care of so that fusion target designs be done. A brief description on self-generation of magnetic field is discussed below.

Self generated magnetic field

A self generated magnetic field in the corona of laser produced plasma has been an important phenomenon. It has been started with great interest in many laboratories since 1970's. For diagnostics of magnetic field in laser plasma, phenomenon known as Faraday rotation is employed. The plasma density and the magnetic field strength determine the amount of rotation. Zeeman effect is another optical method for the same.

The first report on detecting mega gauss magnetic fields was of Stamper of US Naval Research Laboratory when plasma at the surface of a solid target was exposed to powerful pulses of a Nd glass laser. The report was based on the measurement of the Faraday rotation of the polarization plane by plasma probing laser beam near the surface of the target (Stamper and Bipin 1975). Similar work has also been carried by Raven *et al.* (1978) in Rutherford Laboratory, UK.

Interferrometric measurements of the distribution of electron density in the plasma corona using slab, spherical and wire targets at irradiance of 10^{16} W cm^{-2} and wavelength 1.06 µm (Nd laser) showed strong steepening near the critical density. From these experiments it is concluded that strong toroidal shaped magnetic fields are generated at a distance approximately corresponding to the position of the critical density surface. These toroidal fields have closed lines of force embracing the axis of the incident laser beam. Soon after the experimental report of Stamper and Bipin (1975) on the measurement of magnetic field, thermoelectric mechanism has been suggested for the generation of the magnetic field. Also intensive numerical simulation has been launched to study this effect. Thermoelectric mechanism suggest that when the gradients in density and temperature are non collinear, a magnetic field will spontaneously builds up in the plasma.

There are two approaches to obtain self-generated magnetic field in laser plasma. First approach is to solve the evolution equation. This equation for the self generated magnetic field can be derived by combining generalized Ohm's law and Maxwell's equations, the equations of magnetohydrodynamics (MHD), namely the momentum conservation equation. In MHD approximation plasma is considered as electrically conducting perfect gas where details of interaction between ions and electrons are neglected. The evolution equation consists of many terms, which are responsible for self-generation of the magnetic field such as convective, diffusive, source, Hall term, thermal force and radiation pressure term. Since it is a non linear equation, it is difficult to solve full equation and is effortless. In practice only certain terms are considered dominant such as convective, diffusive and source terms (Jha and Srivastava 1986).

In the second approach a different model is used in which effect of pondermotive force has been included. When high power laser beams are applied to plasma, the force due to radiation pressure is coupled to the particles non linearly and the force is termed as pondermotive force (Ghimire and Jha 1996). In the case of s-polarized light, this radiation pressure effect gives rise to EMF, which in turn produces current density and excites the magnetic field. Because of the fact that steep gradients of temperature as well as density are created in plasma it has been shown that large order of megagauss (MG) magnetic fields are generated.

In a short pulse laser of finite spot size with amplitude modulation in time, laser exerts a time dependent curl free ponderomotive force on the electrons. When equilibrium plasma density has a gradient normal to ponderomotive force, electron current density is irrotational, producing a quasistatic magnetic field. With the development of ultra-intense short pulse laser, a new parameter regime has been opened up in the study of non-linear laser plasma interaction. The numerical simulations have revealed extremely high self generated magnetic fields of the order 250 MG in the interaction of ultra-intense laser pulse with over dense plasma target. It has been argued that generation of such extremely high magnetic field is the result of DC current driven by spatial gradients and temporal variations of the pondermotive force of the laser light on the plasma electrons. The DC magnetic field is found to be the same order of magnitude as that of oscillating magnetic field of the laser.

Such intense magnetic fields can also be explained by a very attractive mechanism in which non-uniform intense laser beam interacts with non uniform collissionless plasma having equilibrium electron temperature and density gradients. With the relativistically intense laser pulse, two spatially separated toroidal magnetic fields in the megagauss range have been detected with Faraday rotation. In the outer region of the plasma, conventional thermoelectric field has been observed and a field with the opposite orientation closely surrounding the propagating axis is observed. It can be pointed out that magnetic field can be generated in a non-linear medium if the intensity distribution of the incident electromagnetic beam is radially inhomogeneous. Due to pondermotive force, a radially inhomogeneous laser beam drives a plasma current which in turn produces an azimuthal (with respect to beam axis) DC magnetic field.

Discussion

A brief informative account of the fundamentals of plasma physics, its importance in the studies of fusion energy and self generated magnetic field have been presented in the article. Several other useful applications of academic and technological interests are under study these days. Important ones are plasma processing, surface treatment, space propulsion, reconnection, turbulence etc. Present article may be useful in defining path to interested researchers to understand the concepts about these applications. ■

References

Chen, F. F. (1974). *Introduction to plasma physics.* Plenum Press, New York

Duderstad, J. J. and G. A. Moses (1982). *Inertial confinement fusion.* John Wiley and Sons

Ghimire, A. and L. N. Jha. (1996). *Proc. International conference on plasma physics*, pp. 1666, Nagoya

Goswami, S. N. (1995). *Elements of plasma physics*, New Central Book Agency Pvt. Ltd., Calcutta

Jha, L. N. and M. P. Srivastava (1986). *Contribution to plasma physics.* **26:** 2083

Mukhin, K. N. (1987). *Experimental nuclear physics*, Vol. I. Mir Publishers, Moscow

Nakarmi, J. J. (1999). *Study of magnetic field generation and its effect on the the transport in the corona of laser fusion plasma.* Ph. D. Thesis, Tribhuvan University

Nuckolls, J. *et al.* (1972). *Nature* **239:** 139

Pokhrel, C. P. (1983). *Analysis of parameters in ICF plasma.* M. Sc. Thesis, Tribhuvan University

Raven, A., O. Willi and P. T. Ramsby (1978). *Phys. Rev. Lett.* **41:** 1177

Stamper, J. A. and B. H. Ripin (1975). *Phys. Rev. Lett.* **34:** 138