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Plasmas and Various Nonlinearities, Causing Self Focusing Effect

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ABSTRACT

Non linear effecs have been found to be the overpowering in laser produced plasmas, rf heating of plasmas, laser induced dielectric breakdown, laser-semiconductor interaction, optical fiber communication and several other areas. In plasmas, they arise when the refractive index is an increasing function of intensity due to relativistic mass nonlinearity, ponderomotive nonlinearity or Ohmic heating non-linearity. A Gaussian electromagnetic beam, thus creates a self induced refractive index profile. The axial portion of the wavefront travels with slower phase velocity whereas the marginal rays travel faster and give rise to curvature in the wave front, causing convergence of the beam. When nonlinear convergence supercedes diffraction divergence, the beam self focuses.

Keywords-- Plasma, Nonlinearities, Semiconductor

I. INTRODUCTION

What is Plasma?

Plasma is an assembly of charged particles which can move around freely within the dimension of system. In a gas, electrons and protons are tied to atoms. They are not free to move around independently, hence gas is not Plasma. If we shine light on a gas where

$$h\nu > e\emptyset$$

hv, being the photon energy, -e the electronic charge and $\emptyset$, ionization potential, some of atoms get ionized producing free electrons and positive ions which can wonder independently or freely in the system. The ionized gas is called Plasmas. The earth's ionosphere, extending from a height of 80km to 1000km above the Earth's surface, is an example of Plasma produced via photo ionization by the ultraviolet spectrum of sun light.

II. VARIOUS TECHNIQUES FOR PRODUCTION OF PLASMA

Plasma can also be produced by heating a gas, like a flame, or by bringing it in contact with a hot surface. In a MHD power generator, liquid petroleum gas (LPG) and oxygen mixture, emerging from a nozzle with large velocity, burns to produce a flame plasma. The electron density and electrical conductivity of the plasma can be increased considerably by spraying a powder of low work function material.

Another commonly used technique of plasma productions is DC or rf electrical discharge. A low pressure gas is enclosed within a glass or stainless steel enclosure, called vacuum chamber. A DC potential difference is applied across two electrodes inserted inside the chamber. A tiny number of free electrons, which always exist in a gas at finite temperature, get accelerated by the electric field. When they gain sufficient kinetic energy

$$E > e\emptyset,$$

they ionize atoms on collisions. The newborn electrons also get accelerated ionizing the gas further leading to breakdown. In a tokamak, a fusion device, one can have a fully ionized plasma of 10^7 by ac discharge. Microwaves may also be used to heat the free electrons and achieve avalanche break down of gases.

Freely moving electrons are also encountered in metals and semiconductors, hence these materials are called solid state Plasmas. The electrical and optical properties of these materials are largely determined by the free electrons. Electrolytes, having positive and negative ions may also be viewed as a plasma.

In plasma each ion and free electron experiences coulomb fields of numerous other ions and electrons simultaneously. However, the influence of far away particles can be ignored only that of the neighboring ones needs to be considered.

III. INVENTION OF LASER

The invention of laser in 1960 started new era in research in Physics. In a very short period of time, this field became an independent branch of science. Present day research activities are somehow associated with the use of lasers. Since it's invention, there have been growing efforts for increasing the peak power of the laser systems. The combination of titanium doped sapphire (Ti: S) laser technology with chirped pulse amplification (CPA) technique has set new standards in high power femtosecond pulse generation [1-2]. This scheme basically first stretches the laser pulse in time, amplifies it and then recompressses it. The current laser systems when focused to a $10\mu m$ spot size can produce peak intensities of the

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order of $10^{21} W/cm^2$ at $0.8\mu m$ and $1.06\mu m$ wavelengths [3]. The electric field associated with these laser pulses can be as high as $10^{11} Volt/cm$. In last few years, laser peak power touched petawatt level and it is still growing up in a number of laboratories of the world.

The advances in high power lasers have given a strong impetus to the study of wide variety of nonlinear phenomenona in laser plasma interaction, ranging from nonlinear absorption [4], self phase modulation [5] and self-focusing to parametric instabilities [6], harmonic generation [7], super continuum generation [26] and charged particle acceleration [30]. Recently, it has been shown that high power laser-plasma interaction can generate even shorter pulses [36].

The field of nonlinear optics has grown very fast during the last few years due to availability of high power laser beams. Self-focusing of laser beams occupies a unique place among various non-linear optical phenomenon because of its relevance to other nonlinear effects. Short wavelength lasers are giving rise to newer dimensions to all branches of physics. In plasmas especially, it results in various unexplored nonlinear processes. Understanding these experimental and theoretical investigations in laboratory and space plasmas has been the motivation behind the present thesis.

3.1 Plasma Eigen modes and the Origin of Nonlinearity

An unmagnetised plasma supports three modes of wave propagation: a plasma wave, ion acoustic wave, and electromagnetic wave having dispersion relations respectively, $\omega^2 = \omega_p^2 + k^2 \mathbf{V}_{th}^2$, $\omega \approx kc_S / \left(1 + k^2 c_S^2 / \omega_{pi}^2\right)^{1/2}$, $\omega^2 = \omega_p^2 + k^2 c_S^2$, where ω_p being the plasma frequency, ω_{pi} being the ion plasma frequency and c_S being the ion sound speed. At low intensity, density perturbations and current density are linear function of electric field of wave and waves propagate independent of eachother, obeying the principle of superposition. At high intensity of electromagnetic beam, plasma properties are modified and response becomes nonlinear. The effective plasma permittivity becomes a function of wave amplitude, leading to self focusing, self phase modulation and nonlinear absorption. At non-relativistic intensities, there are three kinds of nonlinearities.

3.2 Thermal Nonlinearity

When an electromagnetic beam passes through collisional plasma, the electrons get heated via Brehmstrahlung absorption and gain higher temperature than ions. This modifies the electron temperature dependent collision frequency leading to nonlinear absorption of the wave. A much stronger effect takes place when electromagnetic wave has a nonuniform distribution of intensity. The electron temperature is nonuniform and a pressure gradient force pushes the electrons from high temperature to low temperature regions. The space charge field generated in the process takes ions along, leading to real part of plasma permittivity a function of the wave amplitude. This type of nonlinearity is called 'thermal' nonlinearity. The density perturbation induced in the medium depends on the profile of the intensity variation and gives to phenomena of self focusing, self phase modulation and harmonic generation.

3.3 Ponderomotive Nonlinearity

A laser beam having a variation in intensity along its wavefront exerts a ponderomotive force on electrons, expelling them from the region of higher electric field. The force arises through the Lorentz force and connective term in the equation of motion,

$$\mathbf{F}_{\mathrm{P}} = -m\mathbf{V}\cdot\nabla\mathbf{V} - e\mathbf{V}\times\mathbf{B},$$

where $-e$, m are the electronic charge and mass, $\mathbf{V}$ is the electron oscillatory velocity and $\mathbf{B}$ is the magnetic field of the wave. The ponderomotive force due to an electromagnetic wave turns out to be of the form $\mathbf{F}_{\mathrm{P}} \propto -\nabla |E|^2$, directed opposite to the intensity gradient [41]. This force is much stronger for electrons than ions, owing to the inverse dependence on mass. Hence electrons are quickly expelled out of the region, setting up ambipolar field, which drags ions out to maintain the quasineutrality.

3.4 Relativistic Mass Nonlinearity

The relativistic mass variation of electrons is another vary important source of nonlinearity . The change in electron mass results in the change of the plasma frequency and refractive index. This nonlinearity is important in intense short pulse laser plasma experiments.

IV. SELF FOCUSING OF WAVES

Self focusing and filamentation have been found to be overpowering effects in high electromagnetic wave propagation in plasmas . Self focusing takes place when index of refraction, $\eta = 1 - \omega_p^2 / \omega^2$, is an increasing function of intensity. For a Gaussian beam, the axial portion of the wave front travels with slower phase velocity whereas the marginal rays travel faster and give rise to curvature in the wave front, causing convergence of the beam. When nonlinear convergence supercedes diffraction diverge, the beam self focuses (c. f. Fig. 1.1).

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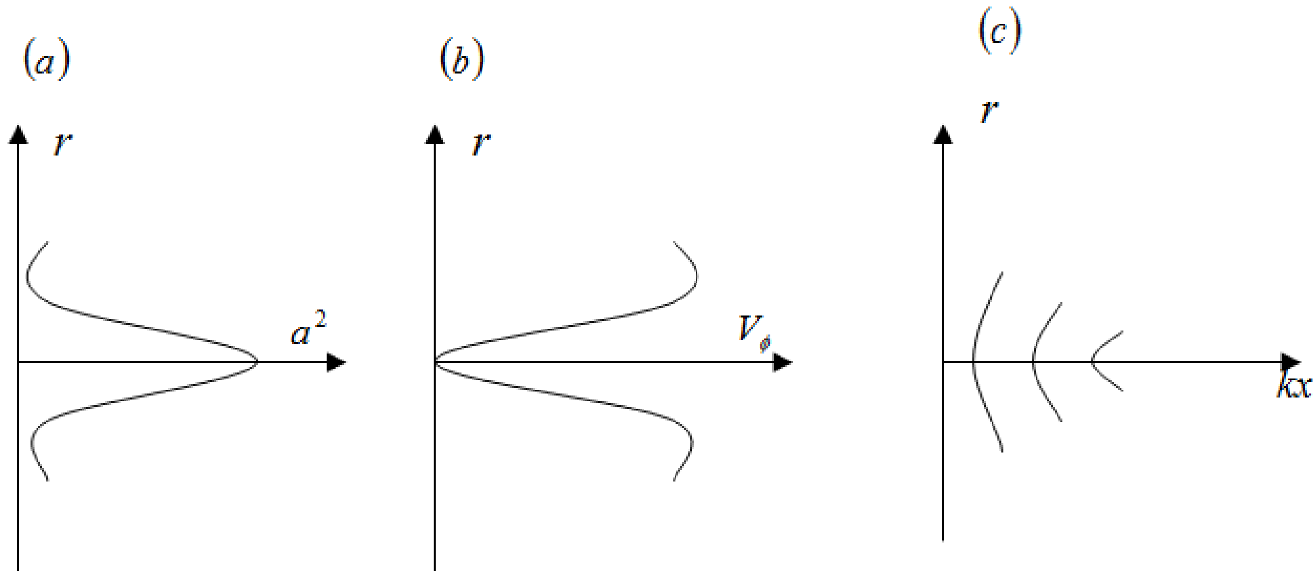

Fig. 1.1 (a) Laser amplitude profile (b) The phase variation (c) The bending of curvature and self focusing of the laser beam.

In the case of a large initial spot size a small perturbation along the wavefront leads to modulation of the refractive index. The portion of the wavefront where intensity is maximum travels with minimum phase velocity while adjoining portions move with faster phase velocity. Thus the wavefront acquires a curvature attracting energy from the neighborhood towards the intensity maximum. This leads to the growth of intensity perturbation and the beam breaks into filaments [c. f. Fig. 1.2).

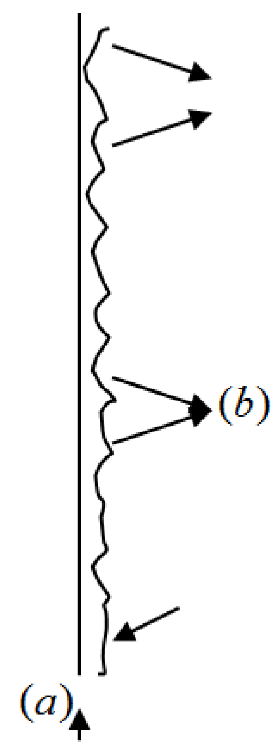

Fig. 1.2 (a) Laser wavefront (b) Intensity perturbation

Earlier studies of filamentation instability considered ponderomotive and Ohmic nonlinearity.

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V. CONCLUSION & DISCUSSION

The advances in high power lasers have given a strong impetus to the study of wide variety of nonlinear phenomenona in laser plasma interaction, ranging from nonlinear absorption. Recently, it has been shown that high power laser-plasma interaction can generate even shorter pulses.

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