CHAPTER-1
INTRODUCTION AND OVERVIEW

1.1 INTRODUCTION

After the discovery of self-focusing of light by Askaryan in 1962 [1], the process of self-focusing of laser beam in plasma is of great importance for various applications like plasma based charged accelerators [2, 3], laser-driven fusion [4], x-ray lasers [5-7], laser electron acceleration [8-12], fast igniter concept of inertial confinement fusion [13-15], ionospheric modification [16-19] etc. So laser beams have always been an interesting area of research for many years which has inspired theoretical and experimental interest [2-12]. To preserve such an efficient interaction of laser beams with the plasmas, it is necessary for these beams to propagate in plasma over extended distances without loss of energy. Further, for the above mentioned applications and to guide the laser beam, preformed plasma channels are necessary so that due to natural diffraction the beam in vacuum expands infinitely. Due to recent advances in such laser pulse technology, we are able to focus the laser beam to extremely higher intensities ordering 10^{20} W/cm^2. The investigators choose the propagation of different kind of laser beams profile like Gaussian beams [20], cosh-Gaussian beams [21], Hermite-Gaussian beams [22], Hermite-cosh-Gaussian beams [23-25], Hypergeometric Gaussian subfamily beams [26], cos-Gaussian beam [27] etc. in the plasma. The study of such pulses makes feasibility to analyze an important nonlinear phenomenon like self-focusing. Further, the relativistic nonlinear optical effects are arisen that are most important phenomena to study relativistic self-focusing, thermal self-focusing and ponder motive self-focusing. When the laser power is greater than its critical value, the relativistic effect becomes dominant. However, when it is smaller then the beam diffraction dominates over relativistic self-focusing [105, 144].

There is an increasing interest in these days in investigating the interaction of laser radiations with plasmas. Therefore the study of various phenomena's like self-focusing, self-phase modulation and various instabilities are of prime importance as these phenomena's significantly govern the experiments on various advanced physical events like plasma based charged accelerators, laser driven fusion etc. When a highly powerful laser beam passes through partially ionized plasma it changes its refractive index, which has a linear as well as a nonlinear component. It is the ponderomotive force which makes the electrons to move away out of an axis region and changes the electron density distribution. This further changes the refractive index of plasma medium and hence leads to process of self-focusing [138]. The ponderomotive and relativistic nonlinear effects arise due to the interaction of free electrons of the ionized plasma with the propagating laser radiation. While as the interaction of unionized atoms leads to atomic nonlinearities. The relativistic nonlinearity leads to self-focusing and the ponderomotive nonlinearity leads to plasma density perturbation which in turn is believed to affect the focusing properties of the laser pulse. Further, when the plasma electrons are set to relativistic quiver motion due to intense laser beam, the ponderomotive nonlinearity sets in and leads to electron density perturbation inside the plasma. This perturbation is caused due to $\mathbf{V}\times\mathbf{B}$ force which is exerted by the radiation field on the free plasma electrons. Such nonlinear relativistic effects of the laser beam as it enters through partially stripped plasma have been studied in great detail. However, the effects produced by ponderomotive nonlinearity along with these effects have not been included in many studies. Since both the nonlinearities are in such a way that they change the beam propagation through plasmas, so it is important to study their combined effect [55].

Most of the investigations about the process of self-focusing have been done in unmagnetized plasmas and have neglected the effect of magnetic field. Their self-generation in laser produced plasmas influences the self-focusing and propagation of laser beams by modifying the dielectric permittivity of plasma [139, 140]. However taking in to account the relativistic electron mass variation, field aligned magnetic perturbations and static density in magnetized plasma, the electromagnetic filamentation instability is investigated [141]. The laser beam evolution in cold, magnetized and underdense plasma is studied by using dependent expansion source method. The transverse magnetic field reduces the critical power which is a basic need for the beam to self-focus [142]. Further, in the Gaussian laser beam evolution in collisional warm magnetoplasma, self-focusing strength is increased. The oscillation period of beam width parameter decreases due to increase in collision frequency. With this the self-focusing occurs faster in comparison to the stationary oscillation regime without the collision frequency [143]. With the availability of high power laser systems and an increasing interest in laser induced fusion generation, most of the investigators have used the fundamental Gaussian beam and simplest class of relativistic case of reference. This makes it possible to inquire the fascinating nonlinear process such as self-focusing. Furthermore, the interaction of lasers with semiconductors has been considered an important and captivating field for many decades. The nonlinear phenomena's are also due to the semiconductors [20] which act like a medium. The fact that self-focusing is being observed in semiconductors is of great pertinence to possibilities of optical limiting devices and various practical applications. In the equilibrium condition, the temperature of the free carriers and that of the crystal is almost same so that the net exchange of energy between them is zero. In the steady state, with the application of electric field, the free carriers gain energies and results in higher temperature than that of the crystal [63]. This change in carrier temperature leads to corresponding change in the effective mass of carriers which plays a captivating and an important role for self-focusing in semiconductors [24]. Thus, the interaction of lasers with semiconductors continues to be a front line area of research.

Most of the electromagnetic beams have a non-uniform distribution of irradiance along the wave-front. This non-uniform distribution of irradiance has been taken in to account in harmonic generation. It is well known that these beams show the phenomenon of self-focusing/defocusing. Also, for non-uniform irradiance distribution and for a given power of the beam, it is found that the average of the power of the electric vector in the wave-front is much higher than that for uniform irradiance distribution. Hence, in the case of non-uniform irradiance, the magnitude of the generated harmonic is higher. This provides a strong motivation for the study of the growth of the harmonics in plasma when self-focusing is taken in to account [145]. Therefore, the propagation of electromagnetic waves having non-uniform intensity distribution through plasmas is a problem of considerable importance. Since, at low power densities diffraction causes divergence of the wave while as this picture is changed drastically at high power densities. Furthermore, in laser plasma interactions which involve high intensities, a laser beam can overcome natural diffractive defocusing and can remain focused via its own nonlinear interaction with the plasma [144]. The self-focusing effect can be produced due to the relativistic mass increase of electrons, change in the refractive index and also due to density perturbation caused by radiation or thermal pressure [20, 106].

1.2 SELF FOCUSING OF LASER BEAM

The process of self-focusing of laser beams in plasmas has been considered a subject of extensive study over the last few decades [146]. It has wide applications in energy fusion driven by lasers, laser wake-field acceleration, beat wave accelerator, x-ray lasers etc. When a Gaussian laser beam propagates in non-linear medium like plasma, the intensity is greatest on the axis of the medium and the index of refraction would be greater on the axis than off the axis of medium. Due to such induced refractive index variations the wave front of the laser acquires a curvature and hence tends to focus. The process is known as self-focusing. In other words it is a nonlinear process that has been produced by change in the refractive index of materials when made visible to electromagnetic radiations. It is frequently observed when generated radiation (by femto second laser) propagates through many solids, liquids and gases. It is also caused by the intensity dependent refractive index, $\partial\eta/\partial|E|^2 > 0$ which arises due to relativistic mass effect, ponderomotive force, non-uniform ohmic heating [147] and subsequent plasma diffusion. At an instant when relativistic nonlinearity arises, it requires very high laser intensity so that the electron quiver velocity becomes comparable to the velocity of light in vacuum (v~c) [146]. Because of the various mechanisms that produce refractive index variations, in turn result in self-focusing. There are two main cases in self-focusing which are as follows.

1.2.1 Kerr–induced self-focusing: This type of self-focusing is brought about by the modification in refractive index of the materials when electromagnetic radiations are made incident up on them. Optical Kerr-effect is non-linear process which occurs when an intense electromagnetic radiation interacts with the nonlinear medium, and produces a variation in the refractive index (η) as $\eta = \eta_0 + \eta_2 I$, where η_0 is the linear part and η_2 is the non-linear part of the refractive index [148]. I is called radiation intensity. If the radiation power is greater than the critical power then self-focusing arises and critical power is given by $P_{cr} = \alpha\lambda^2 / 4\pi n_0 n_1$, where λ is the wavelength of the radiation and α is a constant that depends on the spatial initial distribution of the beam.

1.2.2 Plasma self-focusing: The first quantitative field of study for self-focusing of laser radiation was developed for dielectric materials i.e. non-ionized solids, liquids and gases. In advance laser technology, the most interesting area is the observation of self-focusing of laser beams in plasmas. The process of self-focusing is caused by the change in refractive index of the medium, when laser beam propagates through it. There are two dominating contributions [149]. One is the relativistic mass increase of electrons that comes from the quiver motion of electron in the electrical field of the refractive index. It decreases the beam spot size with beam energy focused inward. Another resulting from excitation of electron plasma wave is the force of the beam. The interplay and evaluation of such processes is not a simple task, but the outset relationship for critical power [105, 144]

$$P_{cr} = \frac{m_e \omega^2 c^5}{e^2 \omega_p^2} \approx 17\left(\frac{\omega}{\omega_p}\right)^2 GW$$

Where, ω is the radiation angular frequency of incident laser, m_e is the mass of electron, *c* the speed of light and *e* the electronic charge. The self-focusing can be thermal, relativistic and ponderomotive.

1.2.3 Thermal self-focusing: It arises when the density of perturbation is caused by radiation or thermal pressure, respectively. It is because of collision heating of plasma, due to induced hydrodynamic expansion that leads to an increase in refractive index and hence further heating. It could initiate the process of self- focusing which decreases the filament size and increases the intensity in the filament.

1.2.4 Relativistic self-focusing: This is the nonlinear mechanism for the modification of the refractive index for plasma. Relativistic self-focusing arises due to the mass increase of electrons, which change the refractive index n_{rel} as $\eta_{rel} = \left(1 - \omega_p^2 / \omega^2\right)^{1/2}$, where, ω_p the relativistic plasma frequency.

1.2.5 Ponderomotive self-focusing: The ponderomotive nonlinearity is important to self-focusing. It is due to expulsion of the electrons from the focal spot. Ponderomotive self-focusing is generated in plasma due to ponderomotive force which makes the electrons to move away out of the region having higher intensity, leaving behind a region of lowered electron density and increased refraction index and hence induces a focusing effect. Since the refraction index of plasma depends on the electron density n_e and critical density n_c. It is given as $n = \left(1 - n_e / n_c\right)^{1/2}$

the depletion of electrons at the place where intensity is large raises the refraction index, slows down the phase velocity of the light wave and causes the wave-fronts to acquire curvature so that the light is focused towards the original region of enhanced intensity. So, the light wave energy propagates normal to the curved wave front. So an initial section of the beam with a slightly higher intensity than its surroundings will become more intense as the beam propagates.

1.3 IMPORTANCE OF SELF FOCUSING

The self-focusing effect plays a captivating and crucial role in a number of applications like those of laser-driven fusion, plasma based charged accelerators, x-ray lasers, harmonic generation, electron acceleration in wake-field, inertial confinement fusion etc. It is very undesirable in those applications where compression of fuel pellets can be prevented and provides a method of obtaining high flux densities which are necessary to study laser plasma interactions [35]. It further imposes a restriction on the power which can be transmitted through an optical medium and often leads to damage in optical materials [28]. So, it can be considered as a limiting factor in designing the high-power laser systems. Further, the ponderomotive force which expels radially the electrons of an intense laser beam, lead to cavitation in plasma [48]. In case of collisional plasmas with nonlinear absorption, the nonlinearity in absorption cancels the effect of divergence. The relativistic mechanism manifests itself for intense pico-second laser pulses and makes the study very important. The laser propagates in a periodically focused manner if the laser power is above the critical power and undergoes divergence, if it is below the critical power [105]. The relativistic self-focusing effect is produced due to relativistic mass change. If in plasma, the frequency becomes greater than the natural frequency of electron oscillations, then the electrons will be forced to move away out of the beam field. The focused beam then exerts a radial ponderomotive force on electrons and makes them to move away out of the beam, producing a lower density region which results in focusing of the radiation [28]. Remarkable self-focusing effects have been observed recently with femto second laser beams propagating in the atmosphere and light filaments in the air. From such air filaments (permitting spectroscopy), a broad spectrum of radiation from ultraviolet to mid-infrared is generated in the atmosphere. The entire absorption spectrum can be determined by a single pulse from a portable femto second laser. Another exciting possibility of the use of these filaments containing plasmas is to guide lightning away from sensitive sites.

1.4 IMPORTANCE OF PLASMA DENSITY RAMP

The plasma density ramp or density transition in plasma occupies a crucial and captivating role in laser-plasma interactions as it is used to overcome the defocusing of laser beam [64]. A highly powerful laser beam that undergoes through underdense plasma acquires a very lower spot size due to relativistic effect and hence regular and repeated self-focusing or defocusing of the beam takes place. In order to make the self-focusing effect a bit stronger, density ramp is considered [77, 92, 97, 99]. It is because in the density ramp region, the laser beam detects a narrowing channel and hence in this environment, the oscillation amplitude contracts while as frequency of laser beam increases. Again, electron density being an increasing function of the propagation distance, the dielectric constant of plasma decreases rapidly as the laser beam deepens in to the plasma. With the result, the laser beam gets more focused and hence self-focusing effect is enhanced [22, 85]. Further, to abstain the laser from defocusing and to observe better and maximum focusing nature, the length of the density ramp is to be increased in an underdense plasma [64]. So, plasma density ramp has a captivating role in making the self-focusing effect stronger. The gas jet plasma based experiments observe such a kind of plasma density ramp. The magnetic fields along with the density ramp have also been found to increase the focusing capacity of beam [65, 91, 93, 102]. In other words, the magnetic field is found to act like a catalyst for self-focusing phenomenon [65]. This scheme forms a basis for various laser-driven applications as the laser beam not only is focused but propagates up to a long distance without divergence.