CHAPTER-1

INTRODUCTION AND OVERVIEW

1.1 INTRODUCTION

After the discovery of self-focusing of light by Askar’yan in 1962 [1], it become the most fascinating and interesting area of research. The interaction of light with plasma [2-4], cluster [5, 6], liquid [7] etc. has been widely studied by the researchers and scientist due to its socially useful applications like x-ray lasers and the laser driven accelerators [8], the generation of inertial fusion energy driven by laser [9-11], the production of quasi mono-energetic electron bunches [12], optical harmonic generation [13] etc. These applications need the laser pulse to propagate over several Rayleigh lengths in the plasma or cluster without loss of energy. Today, extremely high intensity of the order of $10^{20}$ W/cm$^2$ produced by short pulse laser technology enabled various high energy related experiments. Investigators choose the propagation of different kind of laser beams profile like Gaussian beams [4], cosh-Gaussian beams [14], Hermite-Gaussian beams [15], Hermite-cosh-Gaussian beams [16-18] etc. in the plasma.

The non-linearity is accountable for self-focusing of light propagating through the non-linear medium as the velocity of light varies in the non-linear medium which causes the self-focusing effect. The relation between velocity of light in the medium and index of refraction is given as $v = c/n$, where $v$ is velocity of light in medium, $c$ is velocity of light in vacuum and $n$ is the refractive index of the medium. As the ray of light propagates from rarer medium to the denser medium, it bends towards the normal to the surface on which ray of light incident.

![Figure1.1: Refraction of light](image)

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Figure 1.1 represents the phenomenon of refraction of light as ray of light propagates from rarer medium to denser medium. Similarly, a ray of light propagating from denser to rarer medium bends away from the normal to the surface. This is the fundamental law of physics and is responsible for the converging or diverging of ray of light propagating from rarer to denser or denser to rarer medium respectively. When an intense laser pulse propagates through plasma, the relativistic nonlinearities or ponderomotive nonlinearities or thermal nonlinearities lead to self-focusing of the laser beam. This happens because the plasma density is perturbed by the highly energetic laser beam. Self-focusing/defocusing of laser pulse also occurs in clusters. The interaction of lasers with plasmas, clusters and semiconductors has been a charming field of research for more than fifty years.

Clusters are nanoscale solid density atomic aggregates bound by Vander Waals forces. Their size ranges from \(10^2\)-\(10^6\) atoms. The diameter of the clusters varies in size from a few angstroms to a 1000Å and their density in the gas ranges typically from \(10^{11}\) to \(10^{14}\) clusters/cm\(^3\). Different atomic, molecular and hetero-nuclear species can clubbed together to form clusters. Clusters can be formed by solids, liquids or gaseous atoms, molecules or hetero-nuclear species.

**Figure 1.2: Atoms or molecules clubbed together by Vander Waals forces to form cluster**

Gas-atom clusters are formed when high-pressure flow of a cooled gas into vacuum results in adiabatic cooling and expansion of the gas and particle aggregation [19]. A clustered gas jet typically consists of solid density clusters and low-density background of un-clustered gas atoms. The characteristics of the clustered gas like the
size distribution, number density of clusters and the ratio of clustered to un-clustered atoms or molecules is determined by the backing temperature, pressure, nozzle geometry and other experimental factors. When clusters are irradiated by an intense laser pulse, it absorbs energy and explodes, leaving behind tenuous plasma. The clustered gas has low volume average density but the clusters themselves are at solid density. Due to this strong interaction of individual clusters with the incident laser beam is observed and it also allows the propagation of the laser beam through the clustered gas. The efficient blending of laser energy with the clustered gases [20] makes clustered gases as a unique medium for studying non-linear interaction with laser beams [21] and it can lead to numerous interesting applications.

The laser-heated clusters efficiently generate x-ray [22] and extreme ultraviolet (EUV) radiation [23-27]. Clusters are debris-free, which is an issue with solid targets and the system takes much less space than the conventional synchrotron radiation source. Hence clusters irradiated with strong laser pulses can be used as an easily-renewable, debris-free tabletop radiation source for many applications like X-ray lasers, X-ray and EUV lithography [24] and X-ray tomography [28]. Explosion of clusters in strong laser fields leads to ejection of high energy electrons and energetic charged ions [29, 30]. This opens up the possibility of using energetic particles from laser-irradiated clusters to seed particle accelerators and for proton beam radiation therapy in cancer treatment [31]. Collisions between energetic ions from exploding clusters can produce neutrons via thermonuclear fusion. Laser irradiated clusters can thus be a future tabletop source of thermonuclear neutrons for imaging purposes. The dynamics of exploding clusters gives rise to interesting nonlinear optical effects such as harmonic generation [32] and self-focusing [33]. Clustered gases are also proposed as targets for creating plasma waveguides and their ability of self-guiding of a laser pulse in plasma and plasma channel formation is the field of interest for laser-based particle acceleration schemes.

As the clusters are formed by the combination of atoms or molecules or heteronuclear species, so it become necessary and interesting to study the behaviour of these assemblies in strong electromagnetic field and investigating the dynamics of laser-clusters interaction and cluster explosion is always be a problem of great interest. Generally, clusters strongly absorb the energy from laser beams and this property of
clusters makes it useful for various applications as mentioned above. Clustered gases, having properties in between that of solid and gas phase, makes it better absorber of laser beams energy and laser beams propagating through clustered gases generates wonderful nonlinear optical effects like self-focusing of laser beams, modulation of pulse spectrum and higher harmonic generation. The present work is dedicated to the study of the effect of self-focusing in plasmas and clusters.

1.2 SELF-FOCUSING OF LASER BEAM IN PLASMA

When a Gaussian laser beam propagates in non-linear medium, the intensity would be the 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 the induced refractive index variations the wave front of the laser acquires a curvature and laser tends to focus. The process is known as self focusing of the beam in a non-linear medium. Self focusing is frequently observed when the radiation produced by femtosecond laser transmits through a number of gases, liquids and solids.

![Figure 1.3: Observation of self-focusing effect of laser beams propagating deeper into the denser medium](image)

When an intense laser beam propagates through plasma, then the refractive index of the plasma is modified and is composed of a linear and an intensity dependent nonlinear component. Self focusing in plasma can occurs through thermal, relativistic and ponderomotive effects and correspondingly it is called thermal self focusing, relativistic self focusing and ponderomotive self focusing. The availability of high power lasers
attracts the attention and interest of the researcher towards nonlinear laser plasma interactions and harmonic generation. There are certain processes which are not assumed to be of great importance earlier because of low available powers of electromagnetic beams and now, these processes become very important in plasma and cluster and are studied by number of researchers. As a very high power laser beam propagates through the plasma, the electron velocity in plasma may become quite large comparable to the velocity of light in free space. Thus, the effect of variation of mass must be taken in to account and it gives rise to the effect of relativistic self-focusing. The relativistic effect of an intense laser pulse propagation through the plasma leads to self-focusing because the dielectric constant of plasma is an increasing function of the intensity and as the intensity of the pulse increases, the index of refraction of the medium also increases. Also, the ponderomotive force of the focussed laser beam pushes the electrons out of the region of high intensity. It decreases the local electron density and increases the plasma dielectric function and it leads to more self-focusing of the laser beams.

Now a day’s researchers focus their attention on the medium with varying density profile. Such medium can be achieved by the application of plasma density ramp. The density of such medium can be assumed to enhance along the direction of propagation of the laser beam. The plasma density ramp plays a very significant role during laser-plasma interaction. A very high power laser beam transmitting through plasma with varying density profile shrinks and can attain a least spot size due to self-focusing effect. After the focusing of the beam, the nonlinear refraction starts dwindling and hence, the beam waist of the laser beam starts increasing. Thus one may observe the self-focusing and defocusing effect of the laser beam with the distance of propagation. In order to get rid from the defocusing of laser beam, one can apply localized upward plasma density ramp. Thus the laser beam obtains a least beam waist and maintains it till longer distance along the direction of propagation. The plasma density ramp could be very useful for the strong self-focusing of a high power laser by the proper selection of laser and plasma parameters. With the increase in plasma density, the self-focusing ability of laser beam becomes stronger because as the laser beam penetrates deeper into the density ramp region, it observes a slowly narrowing channel and thus, in this region, the fluctuating amplitude of the spot size contracts, while its energy enhances. Also, it is well known fact
that the equilibrium electron density is an increasing function of the distance of propagation of the laser beam so the plasma dielectric constant decreases quickly as the beam penetrates deeper inside the medium. Due to it, the self-focusing effect is enhanced and one may observe strong focusing of the laser beam. In case of underdense plasma, the minimum plasma density is chosen. The proper length of plasma density ramp is assumed to avoid the utmost defocusing of the laser beam. But the plasma density should not be considered to be much larger; otherwise, the laser beam can be reflected back and propagation of the laser beam become complicated. So, proper selection of plasma density ramp plays an significant role to make the self-focusing stronger.

The application of magnetic field in the plasma region can affect the self-focusing ability of the laser beam. Thus the study of the propagation of a high power laser beam through plasma with a density ramp where a magnetic field is also present becomes more important and interesting. The collective effect of the plasma density ramp and the magnetic field increases the self-focusing ability of the laser beam in plasma. The beam waist of the laser beam contracts as the beam propagates deeper inside the plasma due to the effect of the plasma density ramp. The application of magnetic field acts as a strong tool to enhance the self-focusing effect of the laser beam during propagation in a plasma density ramp. The simultaneous application of plasma density ramp and magnetic field converge the laser beam strongly. In this kind of experimental model, the laser beam can propagate over a long distance without divergence and hence, this scheme is useful in many laser-driven applications.

1.3 SELF-FOCUSING OF LASER BEAM IN CLUSTER

Self-focusing in clusters is also an important phenomenon to be studied numerically and analytically. If a gas expands out of a nozzle into vacuum, the expanding gas becomes supersaturated and forms condensed molecular beams or cluster beams where the atoms or molecules are held together by Vander Waals forces. An atomic cluster is an intermediate form of matter with particle densities comparable to that of bulk solids. As the highly intense laser beam propagates through the cluster, there occur many non-linear optical effects like self-focusing of laser beams, modulation of pulse spectrum and higher harmonic generation. Since the clusters strongly absorb the energy from laser
beams, so this property of cluster makes it useful for various applications. A highly intense laser converts the clusters into high electron density plasma balls which may expand quickly under hydrodynamic expansion or Coulomb explosion [34, 35]. The electron response to the laser increases in the expanding clusters due to decrease in electron density [36]. It give rise to many exciting phenomena’s like self-focusing [33], generation of harmonics and x-rays [22], strong absorption of energy [37], production of energetic neutrons [38] etc. The electrons of each cluster undergo oscillatory displacement and these electrons execute large excursions in the laser and spend a considerable part of time outside the cluster and the cluster acquires a positive charge. Coulomb explosion of these clusters produces energetic ions. A gas containing clusters may also contain free atoms. Our emphasis will be on analytical and numerical study of self-focusing of a short pulse laser in plasmas and clusters.

1.4 TYPES OF SELF-FOCUSING

There are three kinds of self-focusing of light namely relativistic self-focusing, ponderomotive self-focusing and thermal self-focusing. These are briefly defined as below:

1.4.1 Relativistic Self-Focusing

Relativistic self-focusing effect arises due to the variation in the electron density in plasmas caused by the propagating laser pulse of extremely high intensities of the order ranging from $10^{17} - 10^{20}$ W/cm$^2$. The high intensity laser pulses provide sufficient energy to the constituents like electrons of the plasma or cluster which cause an electron oscillatory velocity comparable to the velocity of light. Thus the mass of electron, oscillating at relativistic velocities in laser field, increases by a factor given by $\gamma = 1/\sqrt{1 - v^2/c^2}$ and give rise to non-linearity due to which the relativistic self-focusing effect occurs.

1.4.2 Ponderomotive Self-Focusing

This kind of self-focusing effect is caused by ponderomotive forces, $F = (\varphi_p^2/\varphi^2)^\gamma (e_0E^2/2)$. The ponderomotive force acting on electrons takes place due to
the drifting of the electrons in an inhomogeneous field and the interaction of drift velocity of electron with the magnetic field. The electrons undergo strong repulsion from the region of maximum intensity to the region of minimum intensity due to the action of ponderomotive forces and it decreases the local concentration of electrons density in plasma. It increases the plasma dielectric function and laser beams become more self-focused in plasma.

1.4.3 Thermal Self-Focusing

Thermal self-focusing occurs due to the thermal heating of the medium. It occurs due to collisional heating of plasma exposed to high energy laser beams. The high energy laser beams increases the temperature and the increased temperature causes an expansion which causes to an increase of refraction index of the medium. The variation in refractive index of the medium gives rise to nonlinear effects. Thus a laser beam propagating through this medium undergoes strong self-focusing.