STUDY ORIENTED PROJECT REPORT

LASER MATTER INTERACTION

Under guidance of

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TABLE OF CONTENTS

INTRODUCTION

The Laser is an outgrowth of a suggestion made by Albert Einstein in 1916 that under the proper circumstances atoms could release excess energy as light—either spontaneously or when stimulated by light.

What Einstein had theorised had a huge impact on humanity and it has played a very big role in development of various technologies. Lasers are used in various tools such as:

Optical disk drives, Laser printers, barcode scanners, DNA sequencing instruments, fibre-optic, semiconducting chip manufacturing , Laser surgery and skin treatments, cutting and welding materials, military and law enforcement devices for marking targets and measuring range and speed, and in Laser lighting displays for entertainment and many more.

Lasers have all sorts of uses from the Laser in your optical disc drive and your printer to the Laser in used in LIGO (Light Interferometer Gravitational observatory) Lasers are used in daily mundane objects and in highly precise scientific observatories.

Laser printer

(LIGO)

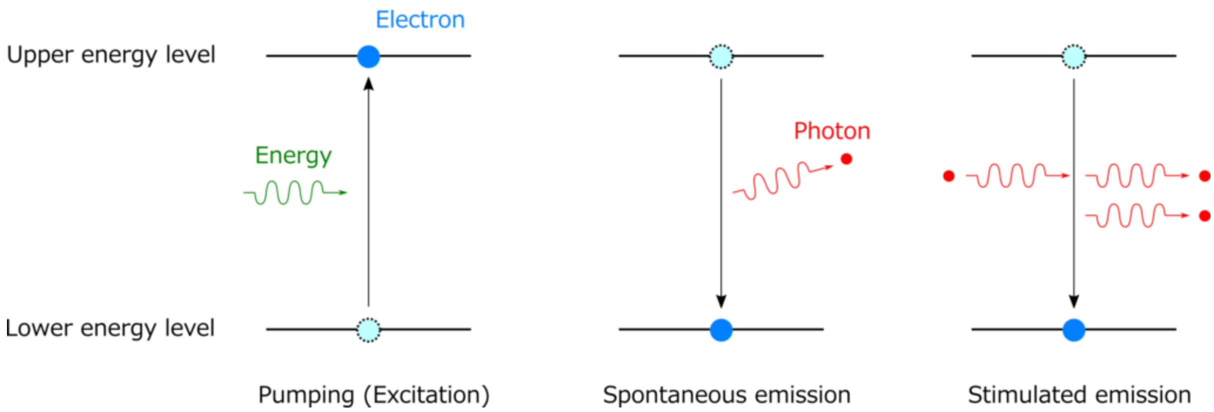
Lasers are vastly used devices and hence how one works can be really helpful to learn and understand. In this report I will explain what a Laser is, how a Laser works and what happens when Laser or light, at various intensities interacts with matter.

Lasers

The word Laser is an acronym that stands for "light amplification by the stimulated emission of radiation". Lasers are essentially highly directional, highly intense, highly monochromatic and highly coherent optical sources. The principle on which Lasers work is known as Stimulated emission. Stimulated emission was postulated by Einstein as early as in 1916.

<u>But how does a Laser work (Stimulated emission)?</u>

Laser emission is shaped by the rules of quantum mechanics, which limit atoms and molecules to having discrete amounts of stored energy that depend on the nature of the atom or molecule. The lowest energy level for an individual atom occurs when its electrons are all in the nearest possible orbits to its nucleus. This condition is called the ground state. When one or more of an atom's electrons have absorbed energy, they can move to outer orbits, and the atom is then referred to as being "excited." Excited states are generally not stable; as electrons drop from higher-energy to lower-energy levels, they emit the extra energy as light.



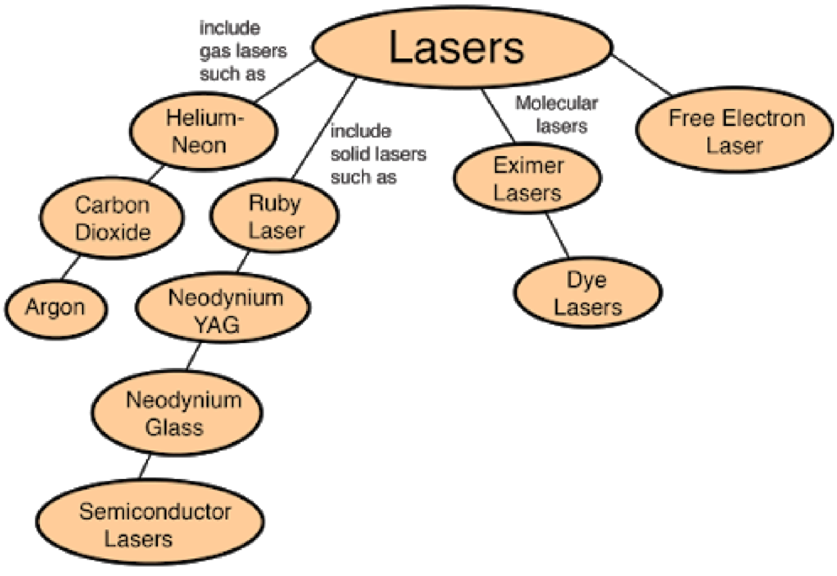
This emission could be produced in two ways. Usually, discrete packets of light known as photons are emitted spontaneously, without outside intervention. Alternatively, a passing photon could stimulate an atom or molecule to emit light—if the passing photon's energy exactly matched the energy that an electron would release spontaneously when dropping to a lower-energy configuration. Which process dominates depends on the ratio of lower-energy to higher-energy configurations.

Ordinarily, lower-energy configurations predominate. This means that a spontaneously emitted photon is more likely to be absorbed and raise an electron from a lower-energy configuration to a higher-energy configuration than to stimulate a higher-energy configuration to drop to a lower-energy configuration by emitting a second photon. As long as lower-energy states are more common, stimulated emission will die out.

However, if higher-energy configurations predominate spontaneously emitted photons are more likely to stimulate further emissions, generating a cascade of photons. Heat alone does not produce a population inversion; some process must selectively excite the atoms or molecules. Typically, this is done by illuminating the Laser material with bright light or by passing an electric current through it.

There are different types of Lasers used in various technologies and fields of science. They are:

1) Solid state Laser	Ruby Laser
2) Gas Laser	Co2 Laser, He-Ne Laser
3) Liquid Laser	Europium chelate Laser
4) Dye Laser	Coumarin dye Laser
5) Semiconductor Laser	Inp Laser



Laser matter interaction

The interaction of Laser with matter depends on how intense the Laser is. If the intensity is not that high (0.8 - 22.5 mW/cm^2) then the surface of the metal will start emitting electrons (photoelectric effect). If the intensity is increased the metal will start to heat up and radiate heat (conduction of heat). Increase the intensity and the metal starts to get liquified. At even higher intensities the metal gets vaporised($10^6 W/cm^2$).

Now comes the interesting part, at intensities of the order 10^9 W/cm^2 the surface electrons and the electrons produced by multiphoton ionisation start absorbing the Laser light and form plasma. Subsequent Laser light heats up the plasma and produces more plasma from the target.

Plasma

Plasma is basically ionised gas. Ionization, is the process by which an atom or a molecule acquires a negative or positive charge by gaining or losing electrons Ionization in case of Lasers happens due to heating. However, if we think about it In space the temperature is very low how then, is the universe >99% Plasma?

Plasma formation in space happens because the number of particles in space is very less what that means is that the particle density is very low in space therefore recombination is hindered and matter remains in the form of plasma.

<u>Definition of plasma:</u>

Although a plasma is described as an electrically neutral medium of ions and electrons, it must satisfy the following three criteria to be called Plasma

1)The plasma approximation: Charged particles must be close enough together that each particle influences many nearby charged particles, rather than just interacting with the closest particle. The plasma approximation is valid when the number of charge carriers within the sphere of influence (called the Debye sphere whose radius is the Debye length) are higher than unity to provide collective behavior of the charged particles.

$$n \lambda_D^3 >> 1$$

This condition ensures that shielding is possible in plasma.

2)The Debye screening length (λ_D) should be shorter than the physical size of the plasma (L)

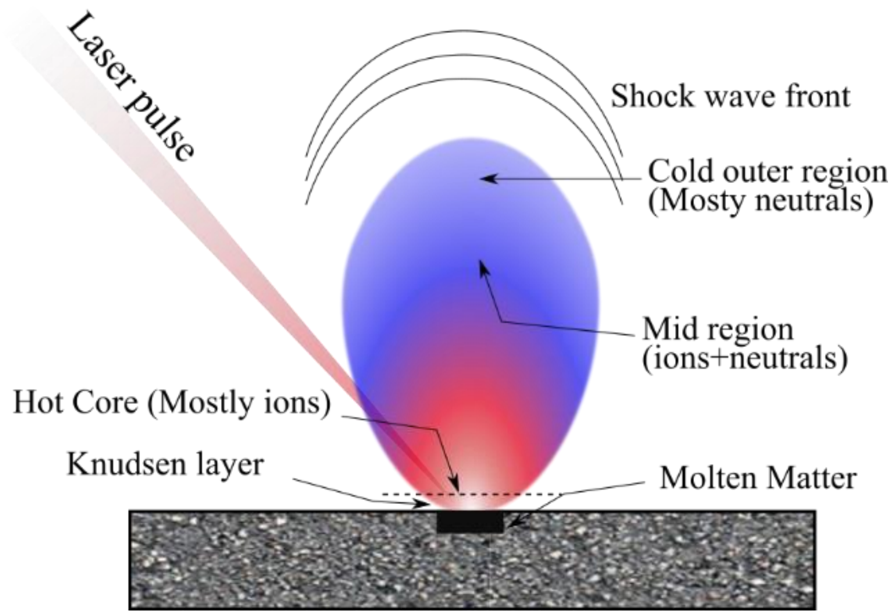
$$L >> \lambda_D$$

As within the Debye length, the plasma can be non-neutral, this condition ensures neutrality of the plasma.

3)Plasma frequency: The plasma frequency (ω_p: measuring the oscillations of the electrons) is large compared to the electron-ion collision frequency (ν: measuring frequency of collisions between electrons and ions; $1/\nu = \tau$ = collision time).

$$\omega_p * \tau >> 1$$

Plasma formation with Laser light



(The Knudsen layer, also known as evaporation layer, is the thin layer of vapor near the matter.)

After the surface of the matter has been vaporised by the Laser light. The vaporised matter absorbs even more light and starts to get ionised This leads to plasma formation Subsequent Laser light heats up this plasma and produces even more plasma the plasma heats up the target material and ablates (fast expansion)

The high intensity Laser has very high electric fields in the focal spot of the Laser which produces air breakdown (dielectric breakdown), that is why, plasma formation using Laser happens usually in vacuum the plasma expands from the target following a monotonically decreasing density profile.

The density profile is decreasing exponentially

$$N = No * e^{-\frac{x}{L}}$$

L here is the Density scale length (length over which the density decreases by a factor of 1/e)

The density profile for any general case is defined to be:

$$L=n/(dn/dx)$$

The density scale length depends on the Laser pulse duration.

For Laser pulse duration of the order of nanoseconds L is almost equal to R, R being thee focal spot radius (100 micro metre).

For sub nanosecond Laser pulses $L \sim C_s t$, where C_s is the sound speed in plasma.

($Cs =[Z kTe / Mi]1/2 \sim 10^4$ m/s)

For $\tau \sim 100$ ps, $L \sim 10^4 \times 10^{-10} = 1\mu m \sim \lambda_L$

For $\tau \sim 100$ fs, $L \sim 10^4 \times 10^{-13} = 1$ nm $<< \lambda_L$

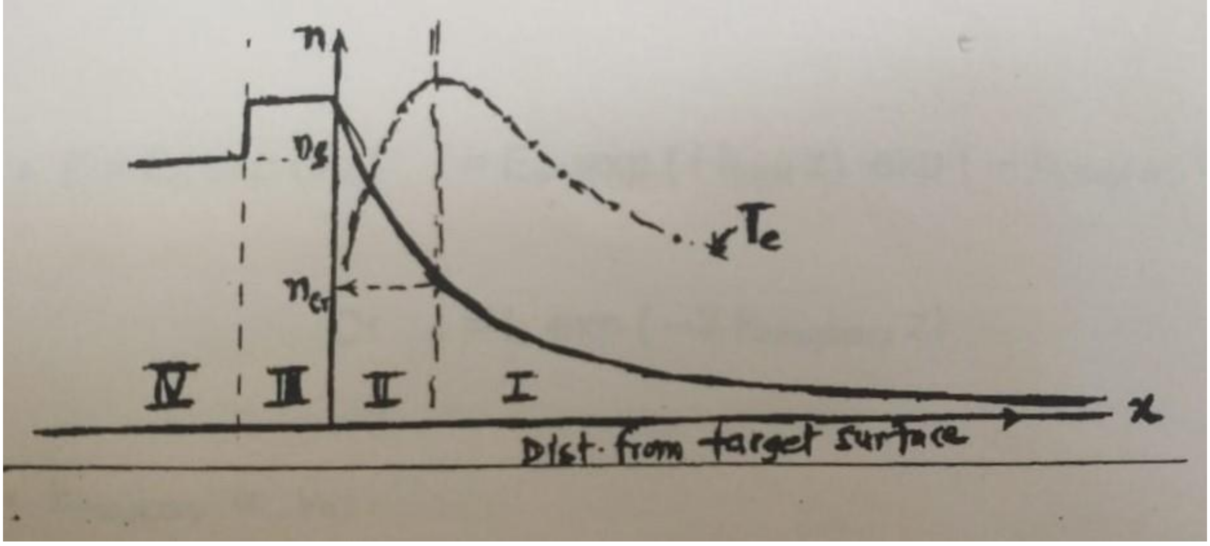
For an electromagnetic wave propagating in plasma, the dispersion relation is given by:

$$\omega^2 = \omega_p^2 + k^2c^2$$

$$\mu^2 = k^2c^2 / \omega^2 = 1 - \omega_p^2/\omega^2 \qquad \text{or} \qquad \mu = (1 - \omega_p^2/\omega^2)^{½}$$

Since light can propagate only if μ is real, hence it is necessary that $\omega^2 \geq \omega_p^2$
In a plasma having density gradient, the above condition implies that the Laser light will penetrate only up to $\omega^2 = \omega_p^2$

The density at which $\omega = \omega_p$ is called the Critical Density



Region I: Underense plasma $n<n_c$ Laser light propagates: Energy Absorption Region

Region II: Overdense plasma $n>n_c$ No light propagation: Energy transport region

Region III: Shock propagation region in solid target

Region IV: undisturbed target region

Mechanisms of absorption of Laser light

These are the following methods by which Laser light can be absorbed by plasma

- Inverse bremsstrahlung absorption.
- Resonance absorption.
- Parametric Decay of Laser light.

Inverse bremsstrahlung absorption

It is analogues to joule heating in a resistor by AC(I^2R) Free electrons oscillate with the external electric field. The uniform oscillatory velocity is randomised by collisions with ions. The motion goes from directed motion to random motion which results in heating. The frequency of collision between particles of two species with mass M1 and M2 with temperature T1 and T2 and charges Z1 and Z2 is given by:

$$\nu_{1,2} = 0.17 n_2 (Z_1)^2 (Z_2)^2 \ln \Lambda / (M_1 M_2 [(T_1)/(M_1) + (T_2)/(M_2)]^{3/2})$$

Where in Λ= coulomb logarithm (5-10 for most plasmas). M1 and M2 are mass numbers Me=1/1836 for electrons. For plasma without electron ion collision the dispersion relation is:

$$k=[\iota/c](1-\frac{\omega_p^2}{\omega_L^2})^{1/2}$$

That is an ideal condition in reality there are collisions which in turn produce heat the equation for that condition is:

$$k = [\omega_L/c]\,(1 - \omega_p^2/\,\mathbf{[\omega_L\{\omega_L + i\,\nu_{e,i}\}]}\,)^{½}$$

$$k = [\omega_L/c]\,[1 - \omega_p^2/\,\omega_L^2\{1 + i\,\nu_{e,i}/\omega_L\}\,]^{½}$$

$$= [\omega_L/c]\,[1 - [\omega_p^2/\,\omega_L^2]\,\{1 - i\,\nu_{e,i}/\omega_L + \ldots\ldots\ldots\}\,]^{½}$$

$$= [\omega_L/c]\,[1 - \omega_p^2/\,\omega_L^2 + i\,(\omega_p^2/\,\omega_L^2)(\nu_{e,i}/\omega_L)\,]^{½}$$

$$= [\omega_L/c]\,[1 - \omega_p^2/\,\omega_L^2]^{½}\;\;[1 + i\,(\omega_p^2/\,\omega_L^2)(\nu_{e,i}/\omega_L)/2\,(1 - \omega_p^2/\,\omega_L^2)\,]$$

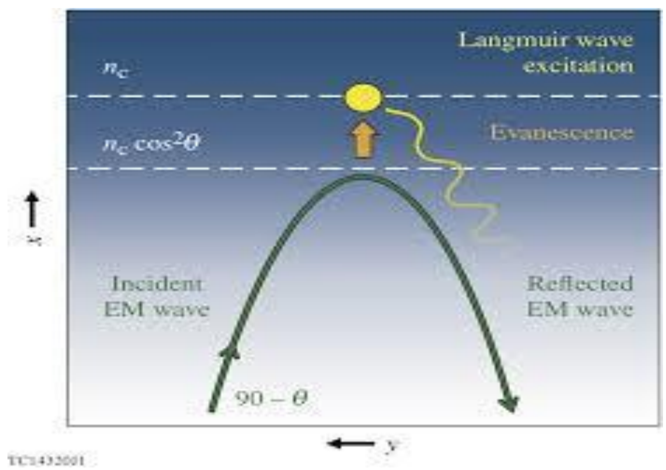
$$= k_{real} + i\,k_{imaginary}$$

$$\text{where } k_{imaginary} = ½\,(\omega_p^2/\,\omega_L^2)\,(\nu_{e,i}/c)\,/\,(1 - \omega_p^2/\,\omega_L^2)^{½}\,]$$

As we can see the k $_{imaginary}$ $\propto$ frequency of collisions

Without collisions there is no absorption of Laser light by Inverse bremsstrahlung absorption.

Resonance absorption



When the Laser beam hits the surface of the matter with an angle (theta) with the direction of the density gradient. By successive application of the snells law we get:

$$\sin(\theta) = \mu_n = [1 - \frac{n_e}{n_{cr}}]^{1/2}$$

$$n_e = n_{cr} \cos^2(\Theta)$$

Total internal reflection is not at the critical density but at a much lower density Larger the angle, lesser will be the absorption by inverse bremsstrahlung as the Laser propagates lesser in the plasma and up to a lower density Though the electromagnetic wave is total internally reflected, the evanescent wave exists in the plasma

The intensity of the wave decays exponentially in the plasma. The component of the amplitude of the evanescent wave at the critical density excites resonance oscillations in the plasma at this density the energy of the EM wave is coupled to the plasma by resonant excitation of the electron plasma waves at critical density. The e.p. waves decay in the plasma to heat up the plasma either by collisional damping (akin to inverse bremsstrahlung mechanism) or by collisionless damping (Landau damping).

Landau damping:

Landau damping occurs because of the energy exchange between an electromagnetic wave with phase velocity v_{ph} and electrons in the plasma with velocity approximately equal to v_{ph} , which can interact strongly with the wave. Those particles having velocities slightly less than will be accelerated by the electric field of the wave to move with the wave phase velocity, while those particles with velocities slightly greater than will be decelerated losing energy to the wave: particles tend to synchronize with the wave.

Since the plasma electrons have Maxwellian velocity distribution

[$n(v) = n_O \exp(-½\ mv^2 / kTe)$], the number of electrons having velocity lower than that of the wave is always more than that of those having a higher velocity. As a result, the electrons will gain net energy from the wave This collisionless process is called Landau damping

Role of density gradient in Resonance absorption:

$$\nabla D = 0$$

$$\nabla.\varepsilon E = 0$$

$$\varepsilon\nabla.E + E\nabla\varepsilon = 0$$

$$\nabla.E = -(E.\nabla\varepsilon)/\varepsilon$$

Excitation of plasma needs charge separation δn_e

$$\nabla.E = -4\pi e\delta ne \neq 0 \text{ (poisson equation)}$$

$$E.\nabla\varepsilon \neq 0$$

$since\ \nabla\varepsilon \propto \nabla ne, hence\ E.\nabla ne \neq 0$

Therefore, the density gradient should be present. The electric field vector must have a component in the direction of density gradient. For a small angle of incidence (for p pol light), the component of the electric field in the direction of the gradient (Esin(Θ)) is less. For spherically polarised light resonance absorption does not happen

At larger angles of incidence, the total internal reflection takes place at lower densities and hence at larger distance from n_{cr}. Hence the amplitude of the evanescent wave at the critical density is smaller, leading to smaller excitation of the ep wave, and hence lower absorption

There exists an optimum angle where the resonance absorption reaches a maximum. This angle is given as:

$$\sin(\Theta)[k_L L]^{1/3} = .8$$

For a large density scale length(L) the resonance absorption occurs in a small range of angles. For a small L, the resonance absorption occurs over a broad range of angles of incidence.

Parametric decay processes

The EM wave can split into two subsequent waves in plasma and these split waves will have an energy equivalent to the EM wave from which it split. These new waves will then transfer the energy in them to the particles by collisional damping or landau damping.

<u>The dispersion relation for various waves in plasma:</u>

EM wave in plasma:

$\omega^2 = \omega_p^2 + k^2c^2$

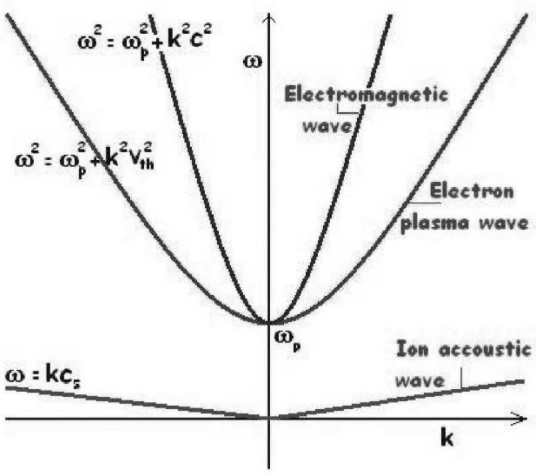
$\omega^2/\omega_p^2 - k^2c^2/\omega_p^2 = 1$

Electron plasma waves in plasma:

$\omega^2 = \omega_p^2 + 3k^2 v_{th}^2 \qquad v_{th} = (kT_e/m)^{1/2}$

Ion Acoustic wave in Plasma:

$\omega^2 = k^2 c_s^2$ $\qquad$ C_s = velocity of sound in plasma



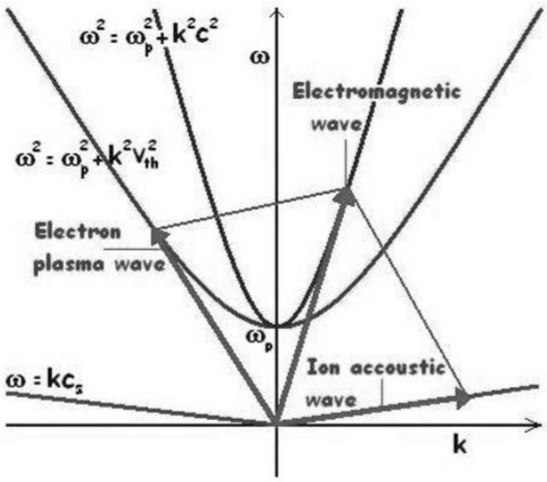
Energy balance	Process name
$\omega_{em} = \omega_{ep} + \omega_{ia}$	*Parametric Decay*
$\omega_{em} = \omega_{ep1} + \omega_{ep2}$	*Two Plasmon Decay*
ω_{em}(incident) = ω_{em}(scattered) + ω_{ia}	*Stimulated Brillouin Scattering*
ω_{em}(incident) = ω_{em}(scattered) + ω_{ep}	*Stimulated Raman Scattering*

<u>Parametric Decay:</u>

$\omega_{em} = \omega_{ep} + \omega_{ia} \quad \Rightarrow \quad \omega_L = \omega_p [1 + 3k_{ep}^2 v_{th}^2/\omega_p^2]^{1/2} + k_{ia} c_s \geq \omega_p$

$\Rightarrow \quad \omega_p \leq \omega_L \quad \text{or} \quad n_e \leq n_c$

Parametric decay instability takes place up to the critical density. Both these plasma waves decay by Landau damping or collisional damping



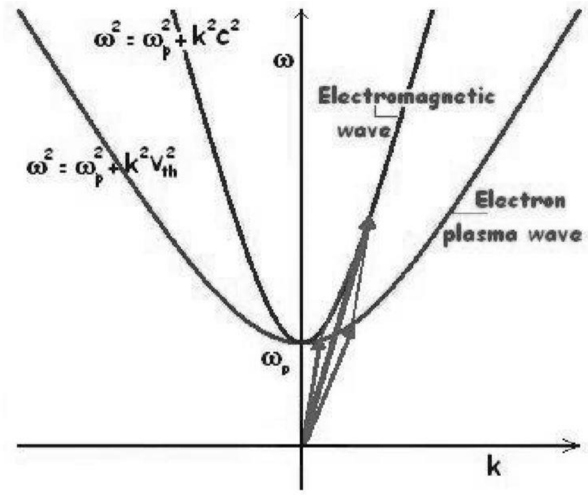
<u>Two Plasmon Decay:</u>

The electromagnetic wave can decay into two electron plasma waves (plasmons).

$$\omega_{em} = \omega_{ep1} + \omega_{ep2} \quad \Rightarrow \quad \omega_L = \omega_p [1 + 3k_{ep1}^2 v_{th}^2 / \omega_p^2]^{1/2} + \omega_p [1 + 3k_{ep2}^2 v_{th}^2 / \omega_p^2]^{1/2} \quad \geq 2\,\omega_p$$

$$\Rightarrow \quad \omega_p \leq \omega_L / 2 \quad \text{or} \quad n_e \leq n_c /4$$

Two plasmon decay takes place near quarter critical density.



Back scattering of Laser light by plasma:

There are two more decay processes which lead to partial absorption and partial back reflection of the Laser light.

These processes are:

1) Stimulated Brillouin Scattering

2) Stimulated Raman Scattering

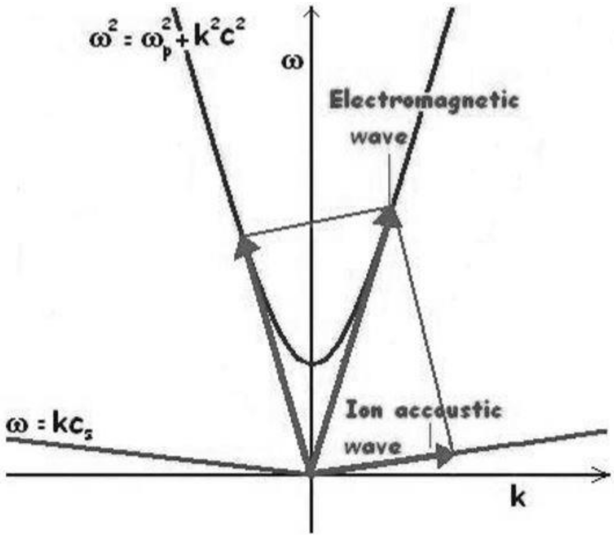
Stimulated Brillouin Scattering

In this process, the incident electromagnetic wave excites an ion acoustic wave in the plasma and the rest of the energy scattered as an electromagnetic wave.

$$\omega_{em}(\text{incident}) = \omega_{em}(\text{scattered}) + \omega_{ia}$$

$$\omega_L = \omega_p [1 + k_s^2 c^2/\omega_p^2]^{1/2} + k_{ia}\, c_s$$

$$\omega_L \geq \omega_p \quad \text{or} \quad n_e \leq n_c$$



This process takes place up to the critical density. **k** of the scattered wave is always in a direction opposite to **k** of the incident wave back scattering of Laser light (conservation of momentum).

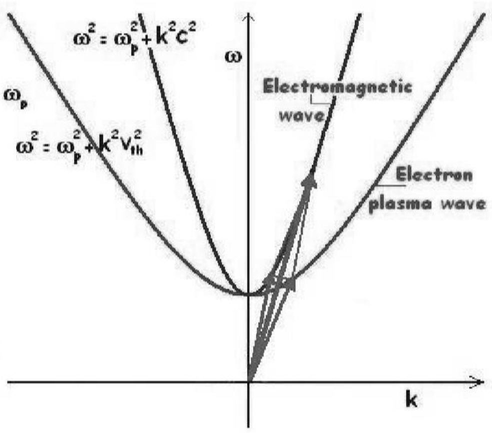
Stimulated Raman Scattering

In this process, the incident electromagnetic wave excites an electron plasma wave and the rest of the energy scattered as an electromagnetic wave.

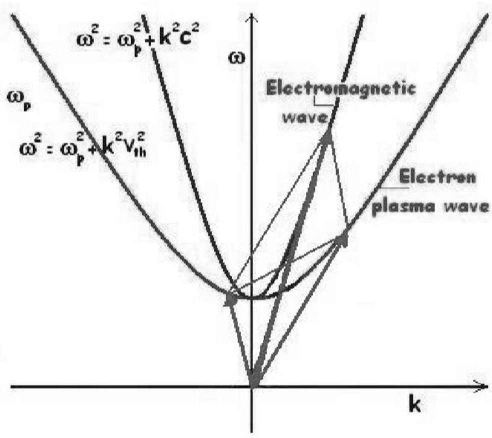
$$\omega_{em}(\text{incident}) = \omega_{em}(\text{scattered}) + \omega_{ep}$$

$$\omega_L = \omega_p \left[1 + k_s^2 c^2 / \omega_p^2\right]^{1/2} + \omega_p \left[1 + 3k_{ep}^2 v_{th}^2 / \omega_p^2\right]^{1/2} \geq 2\,\omega_p$$

$$\Rightarrow \omega_L \geq 2\,\omega_p \qquad \Rightarrow \omega_p \leq \omega_L / 2 \qquad \text{or} \qquad n_e \leq n_c / 4$$



Forward SRS



Backward SRS

This process takes place up to the quarter critical density. **k** of the scattered wave can be in the direction of or opposite to the k of the incident wave forward as well as backward scattering possible unlike in the SBS case. It may be noted that the forward scattered light has a frequency near $\omega/2$ and gets reflected near the quarter critical density

The wave in plasma will scatter the incident Laser light at appropriate frequency satisfying the conservation laws. The incident and the scattered waves will now produce a beat frequency of $\omega_L - \omega_s$ which is exactly equal to that of the plasma wave. The ponderomotive force (to be discussed later) in the longitudinal direction of the beat wave will have a wavelength exactly equal to that of the plasma wave.

As the frequency and direction of the perturbation (due to ponderomotive force) matches with the wave, the wave amplitude will grow. This wave will now scatter more of incident light, thereby increasing the intensity of the scattered light. As a result, the ponderomotive force of the beat wave will increase. Due to this cyclic positive feedback loop, the plasma wave and the scattered wave grow in amplitude at the cost of the incident light. As the incident Laser light stimulates (or drives) the growth of plasma wave as well as the scattered e.m. wave, these processes are called stimulated processes.

SRS and SBS are threshold processes. Since they depend on excitation of plasma waves.

Second Harmonic Generation (SHG) in plasmas

In second harmonic generation $\underline{k}_{2\omega} = \underline{k}_{\omega} + \underline{k}_{\omega}$

$$k_\omega = (\omega/c)\,(1 - \omega_p^2/\omega^2)^{1/2} \qquad \text{and} \quad k_{2\omega} = (2\,\omega/c)\,(1 - \omega_p^2/4\,\omega^2)^{1/2}$$

$$k_{2\omega} = 2\,k_\omega \;\Rightarrow\; (2\,\omega/c)\,(1 - \omega_p^2/\omega^2)^{1/2} = (2\,\omega/c)\,(1 - \omega_p^2/4\,\omega^2)^{1/2}$$

$$\text{or} \qquad (1 - \omega_p^2/\omega^2)^{1/2} = (1 - \omega_p^2/4\,\omega^2)^{1/2}$$

Therefore, $\omega_p = 0$ which means that in plasma, two electromagnetic waves cannot combine to give another electromagnetic wave at twice their frequency.

If the plasma is inhomogeneous (In Laser produced plasma), the electron plasma waves excited resonantly at the critical density can couple non-linearly to give e.m. wave at 2ω

The phase matching condition is $k_{2\omega} = 2\,k_{ep}$

$$\Rightarrow \; (2\,\omega / \sqrt{3}\, v_{th}) \left(1 - \omega_p^2/\omega^2\right)^{1/2} = (2\,\omega/c)\left(1 - \omega_p^2/4\,\omega^2\right)^{1/2}$$

$$\left(1 - \omega_p^2/\omega^2\right)^{1/2} = (\sqrt{3}\, v_{th}/c)\left(1 - \omega_p^2/4\,\omega^2\right)^{1/2} \sim 0 \qquad \text{as} \quad v_{th} \ll c$$

$$\omega = \omega_p \text{ and } n_e = n_c$$

second harmonic generation is possible at the critical density surface.

This process of generation of EM waves at a frequency of 2ω is like the opposite of two plasmon decay where an EM wave splits into two EP waves.

As the electron plasma waves (also referred to as Langmuir waves) are produced by resonance absorption, SHG is maximum when resonance absorption is maximum and takes place in the direction of the reflected beam. As resonance absorption does not take place for s-polarized light, SHG is also minimum for s-polarized light (since in this case $E.\nabla n = 0$)

<u>Importance of density gradient in SHG:</u>

If there is no gradient, then the oscillating electrons (in the e.p. wave) execute a pure simple harmonic motion at frequency ω_L. However, if there is a density gradient, the electrons will see different environment in each half cycle.

Consequently, the amplitude of the electron oscillation in the two half cycles will not be equal. This means that such motion will be highly anharmonic (i.e. periodic but not simple harmonic) and will give rise to higher harmonic radiation. Sharper the gradient, higher will be the anharmonicity, and higher harmonic generation. Hence plasmas produced by short pulse Lasers (such plasmas have very small density scale length) show very bright second harmonic generation.

Ponderomotive Force

A ponderomotive force is a non-linear force that a charged particle experiences in an inhomogeneous oscillating electromagnetic field. In this force the direction of force does not depend on the sign.

$$F_{NL} \propto -\nabla I$$

Lorenz force is given by:

$$\underline{\mathbf{F}} = -e\,\{\,\underline{\mathbf{E}}\,(x,y,z;\, r_1{=}0) + [\,\underline{\mathbf{r}}_1 .\nabla]\,\underline{\mathbf{E}}_{r1=0} + \underline{\mathbf{v}}_1 \times \underline{\mathbf{B}}\,\}$$

$$\underline{\mathbf{F}}_{NL} = -e\,(\,[\underline{\mathbf{r}}_1 .\nabla]\,\underline{\mathbf{E}}_{r1=0} + \underline{\mathbf{v}}_1 \times \underline{\mathbf{B}}\,)$$

This force is known as ponderomotive force it can be further written as:

$$- [e^2 / 4m\omega_L^2] \nabla E^2 \propto - \nabla I$$

With Lasers, one has ponderomotive force in radial direction (due to radial intensity distribution) as well in the direction of propagation (due to pulse intensity variation in time).

In the former case, the ponderomotive force is due to the $- e [\underline{r}_1 .\nabla] \underline{E}_{r1=0}$ term and in the latter, it is due to the $-e \underline{V}_1 X \underline{B}$ term.

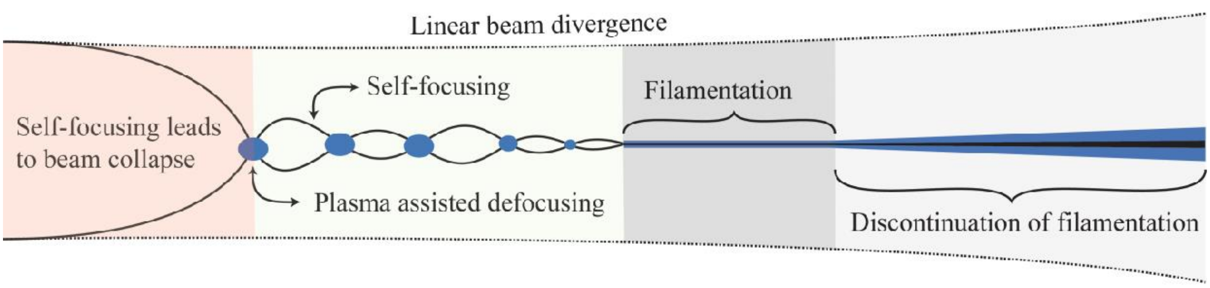
Self-focusing and Filamentation

Consider a Laser beam propagating in plasma and Let the beam profile be Gaussian that is: $I(r) = I_O*\exp(-r^2/r_o^2)$.

Due to the ponderomotive force due to the gradient in intensity, the electrons on the axis of the beam are pushed radially outward. This results in lowering of electron density and consequently an increase in the refractive index near the axis.

As a result of this, the phase velocity decreases near the axis and the wave-front gets retarded on the axis compared to that in the beam wings, leading to a convergent wave front. Due to convergence of the beam, the intensity gradient gets further enhanced , increasing the ponderomotive force. This continues till the whole beam gets focussed.

Since the focussing is due to the beam intensity itself, and there is no external agency like lens to focus the beam, this focussing is referred to as Self Focussing. The self-focussing stops when it is balanced by divergence due to diffraction, which increases as the beam size becomes smaller and smaller ($\Theta \sim \lambda/d$) leading to a uniform width channel.



If the beam has some intensity spikes (hot spots), then at these points, the intensity gradients (and resulting density gradients) are sharp, leading to local focussing of the beamlet. This gives rise to a beam with high intensity filaments on it. This type of self-focussing by which a beam breaks up into several filaments, is called Filamentation.

The filaments can break as the process of focussing is weakened due to loss processes like SRS, SBS etc., which take place at high intensities in the filaments. Filamentation has a much lower threshold than the whole beam self-focussing.

Laser-plasma interaction at ultrahigh intensities

<u>If the pulse duration is long ($\tau > 100$ps):</u>

- Really high energies are required to propagate the Laser for a longer period of time this means it has to be at big laboratories which is inconvenient.
- At high intensities, SRS and SBS start to take place and since density scale lengths are big, SRS and SBS accumulate, leading to back reflection of the Laser light, thereby reducing the absorbed energy.
- Energy flows out of the hot region to surrounding cooler regions, thereby making the effective focal spot larger, leading to lower intensity.
- It is not possible to use long pulse Lasers for reaching $I \geq 10^{15}$ W/cm^2

<u>If the pulse duration is short ($\tau \leq 1$ps):</u>

- The density scale length is very short (λ /10 to λ/1000). Hence SRS, SBS do not get sufficient length in plasma to build up. As a result, losses due to SRS, SBS are minimum.
- No energy transport to the cooler regions during the pulse as the time scale length is much smaller than the energy diffusion time scales.
- Short pulse reduces energy requirement, table top systems possible (commercially available)
- With ultra-short pulse Lasers it is possible to get ultra-high intensities reaching $I \geq 10^{20}$ W/cm^2

Important parameters

Laser Strength Parameter: a_o

The intensity of the Laser electric field is measured in terms of the Laser Strength Parameter "a_o" defined as $a_o = p / m_o c$, where p is the maximum momentum of the oscillating electron.

For an electron oscillating in an electric field $E = E_o \cos \omega t$

$$F = eE$$

$$\Rightarrow p\,(\max) = eE_o/\omega$$

$$a_o = p / m_o c = eE_o / m_o \omega c = eE_o \lambda / 2\pi m_o c^2$$

$$a_o = 0.857 \times 10^{-9} \lambda(\mu m) \sqrt{I(W/cm^2)}$$

$$a_o = p / m_o c = mv / m_o c$$

$$= \gamma \beta = (\gamma^2 - 1)^{1/2} \qquad \Rightarrow \gamma^2 = a_o^2 + 1$$

$$a_o >> 1, \quad \gamma = a_o$$

Ponderomotive energy: U_p

Ponderomotive energy Up is the energy produced by oscillation of an electron due to the electric field. The ponderomotive energy can be written as:

$$= \tfrac{1}{2} m \langle v^2 \rangle$$

$$= e^2 E_o^2 \langle \sin^2 \omega t \rangle / 2 m \omega^2$$

$$= e^2 E_o^2 / 4 m \omega^2$$

$$= 9.33\, I_{14} \lambda(\mu m)^2 \qquad \text{where } I_{14} = I / 10^{14}\ W/cm^2$$

The general formula for the electric field (inclusive of spherical and elliptical waves): $E = \underline{\mathbf{E}}_o(\cos\omega t \underline{\mathbf{X}} + \alpha \sin\omega t \underline{\mathbf{Y}})$

$\alpha = 0$ for linear polarization

$\alpha = 1$ for circular polarization

$0 < \alpha < 1$ for elliptical polarization

$$U_p = e^2 E_o^2 \langle(\sin^2 \omega t + \alpha^2 \cos^2 \omega t)\rangle / 2 m \omega^2$$

$$= e^2 E_o^2 (1 + \alpha^2) / 4 m \omega^2$$

The maximum ponderomotive energy is: $e^2 E_o^2 / 2 m \omega^2$

Expression for ponderomotive force on an electron due to an electric field gradient is:

$$F_{NL} = -e^2 (1+\alpha^2) \nabla E_o^2 / 4 m \omega^2 = -\nabla U_p$$

Hence the name Ponderomotive energy.

Keldysh Parameter: Γ

This parameter determines the relation of ponderomotive energy and the ionization energy. Square of the Keldysh parameter equals the ratio of the ionization potential of the atoms to the maximum ponderomotive energy

$$\Gamma^2 = I.P/U_{pmax}$$

$\Gamma > 1$ I.P. $> U_{pmax}$ Multiphoton ionization

$\Gamma < 1$ I.P. $< U_{pmax}$ Optical field ionization

Multiphoton Ionization (M.P.I.) ($\Gamma > 1$)

Several photons of energy below the ionization threshold may actually combine their energies to ionize an atom. This probability decreases rapidly with the number of photons required, but the development of very intense, pulsed Lasers still makes it possible. In the perturbative regime (below about 10^{14} W/cm^2 at optical frequencies), the probability of absorbing N photons depends on the Laser-light intensity I as I^N.

Energy of free electrons on ionization of an atom with ionization potential I.P. by absorption of multiple photons of energy $h\nu_o$ is given by:

$$\varepsilon = s\, h\nu_o - I.P.$$

such that: $(s-1)\, h\nu_o \leq I.P. \leq s*h\nu_o$ AND $\varepsilon \leq h\nu_o$

Probability of absorption of s photons = $P(s) \propto (1/\Gamma^2)^s$

In experiments on plasma production in gas targets by short pulse Lasers in the intensity range $I \sim 10^{12}$ to 10^{14} W/cm^2, it is observed that:

1) $\varepsilon = (s+n)\, h\nu_o - I.P.$ where $n = 1, 2, 3, \ldots\ldots, n_{max}$ and

2) $n_{max}\, h\nu_o \sim 3$ to $3.5\, U_p$

Which means electrons absorb many more photons than those required to become free on ionization. This process is called Above Threshold Ionization (ATI) by MPI.

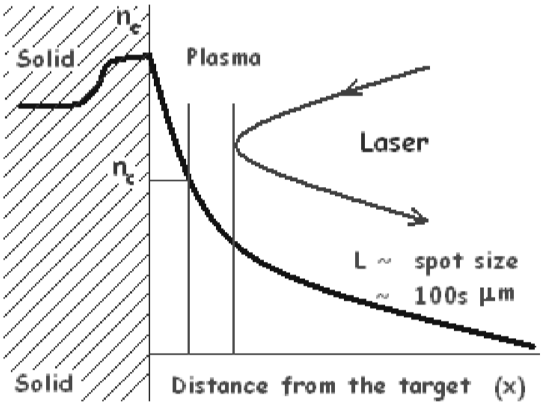
It is also observed in the same experiments that odd harmonics of the incident photon energy are emitted by the plasma (odd harmonic generation)

Harmonic Generation in Solid Targets

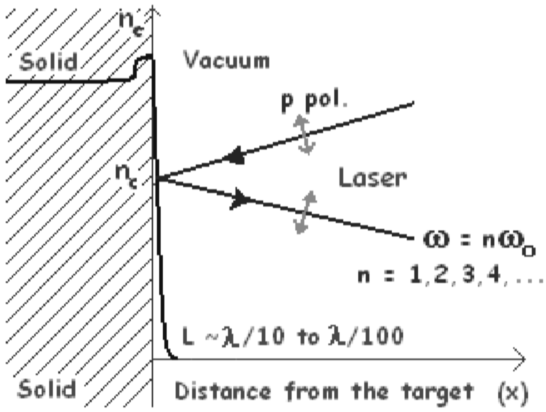
For short pulse Laser produced plasma, the density scale length being a small fraction of wavelength, during oscillations induced by the electric field (by p polarized light), the electron is in the plasma for one half cycle and outside it (in vacuum) for the remaining half cycle. As a result, the motion becomes highly anharmonic, leading to emission of high harmonics

Harmonic generation is in the direction of the Laser light and harmonics emitted only for p-polarized light as for s-polarized light, there is no component of electric field in the direction of the density gradient.

As expected in any interface process, here the inversion symmetry is broken and one gets even as well as odd harmonics, unlike in the case of gases where only odd harmonics are generated.

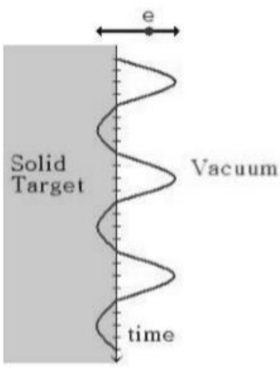


For long pulse Laser



For short pulse Laser

The reason for the presence of even harmonics in this case because the acceleration in the two half cycles is of different magnitudes, and hence there is no exact cancellation of even harmonics produced in one half cycle by those produced in the next half cycle.



It must be noted that the harmonics from solid surfaces are from free electrons, whereas the harmonics from gases are from bound electrons. Intensity of surface harmonics increases with Laser intensity, whereas that of odd harmonics decreases at high intensity. (The latter is due to the fact that higher density of electrons at higher intensity spoils the condition of phase matching of the harmonics). The intensity of the surface harmonics decreases if the Laser has low intensity contrast, as this leads to formation of longer scale length plasma.

ATI by Optical Field Ionization ($\Gamma < 1$)

Here I.P. $< U_{pmax}$ i.e. the electric field energy (ponderomotive energy) is very large compared to the ionization energy. Hence the atoms get ionized by the optical field hence Optical Field Ionization.

In this case also, it is observed that the kinetic energy of the free electron is $> h\nu_o$ like in the multiphoton ionization case which means Above Threshold Ionization.

Beyond Critical Density penetration

Electromagnetic waves propagate in a plasma so long as the refractive index is real. Dispersion relation for e.m. waves in plasma is:

$$\omega^2 = \omega_p^2 + k^2c^2$$

$$\text{Or } k^2c^2/\omega^2 = 1 - \omega_p^2/\omega^2 = \mu^2$$

$$\text{Or } \mu = (1 - \omega_p^2/\omega^2)^{1/2}$$

$$\omega_p^2 = (n_e e^2)/(\varepsilon m) = (n_e e^2)/(\varepsilon\gamma m_o) = \omega_{po}^2/\gamma$$

$$\text{therefore } \mu = (1 - \omega_{po}^2/\gamma\omega^2)^{1/2}$$

E.m. wave can penetrate into the plasma up to $\mu = 0$ i.e. :

$\omega_{po}^2 = \gamma\omega^2$ or $n_e = \gamma\ n_c > n_c$ as $\gamma \geq 1$

Electromagnetic wave having strong field can penetrate in plasma up to a density γ times that at low fields, Beyond Critical Density penetration of light.

Relativistic Self Focussing

If a Laser beam with a Gaussian intensity distribution propagates in plasma, since $\mu = (1 - \omega_{po}^2/\gamma\omega^2)^{1/2}$

The intense portion of the beam sees a higher refractive index than the wings. As a result, a plane wavefront will lag in the centre compared to the sides i.e. the wavefront converges.

Convergence of wavefront leads to higher intensity on the axis and hence more focussing. Focussing stops when finally it is balanced by the divergence due to beam diffraction. This is very similar to the self-focusing we have talked about earlier with a relativistic component to it.

Absorption of ultrashort pulses

Solid targets:

In solid targets, due to short density scale-length (~ $\lambda/100$), there is not much length available for the Laser light to get absorbed by the process of inverse bremsstrahlung. The processes of Raman and Brillouin back scattering are also suppressed due to the small density scale-length.

If the target is kept at slight angle to the Laser beam (instead of normal), then due to small density scale-length, a strong resonance absorption takes place. Even at normal incidence, since the target surface is not smooth on wavelength scale and the density scale-length being even smaller, the Laser light is incident on the surface at different angles (microscopically) and one gets resonance absorption.

Vacuum heating (Brunnel heating) : In the case of ultrashort pulse Lasers, since the plasma density scale length is ~$\lambda/10$ to $\lambda/100$, whereas the amplitude of oscillation of the electrons is ~ λ, hence during each oscillation under the effect of obliquely incident Laser light, the electrons are driven into the solid target, where they get scattered due to collisions with the atoms, thereby heating the target. Also, in one half cycle, since the electrons are in vacuum, this mode of heating is also referred to as Vacuum heating.

Gas targets:

In these targets, the plasma density is several orders of magnitude times lower than in the case of solids. As a result, the inverse bremsstrahlung process is negligibly small. There is no resonance absorption in these targets due to lack of suitable density gradients. The density is always less than the critical density, and hence no “resonance”.

The processes of backscattering are also suppressed here due to small pulse duration, which leads to very little overlap between the backscattered light and the incident Laser light. Forward Raman scattering, however, can take place as the scattered beam co-propagates with the Laser beam. The plasma formation in these targets is mostly due to multi-photon ionization or optical field ionization, depending on the value of the Keldysh parameter at the intensity used.

Cluster targets:

Cluster is a Conglomeration of atoms/molecules to form a nanoparticle of size of 10 to 100nm i.e. Size is much smaller than the wavelength of the light. Clusters can be of gas or solid. Gas clusters are transient but the solid clusters are stable.

Solid clusters:

They are made by ablating a solid target in a background gas. The molten target material under the focal spot, due to recoil from the expanding plasma, gets ejected in the form of tiny droplets, which solidify to give solid nanoparticles.

Gas clusters:

These are made in situ by puffing a gas at high pressure into vacuum. Due to sudden expansion, the gas atoms get cooled and coalesce (due to Van der Waal force) to form gas clusters.

Cluster-Laser Interaction:

Light penetrates into solid to a depth of about a wavelength. Since the size of the clusters << λ the clusters see a uniform electric field. The field inside a dielectric sphere kept in uniform electric field Eo is given by $E = 3\ E_o / (\varepsilon + 2)$

When $(\varepsilon + 2) \rightarrow 0$, the field inside gets highly enhanced. For plasma,

$$\varepsilon = 1 - n_e/n_c; \quad \varepsilon + 2 = 0 \quad \rightarrow \quad n_e/n_c = 3 \quad \text{or} \quad n_e = 3n_c$$

This means that as a cluster is heated from solid density, it will start expanding and as the density reaches three times the critical density (n_c), the Laser field inside the cluster gets highly enhanced and the light gets strongly absorbed. The absorption cross-section for a cluster is given by:

$$\sigma_{abs.} = 4\pi k r^3 \,\mathrm{Im}\left(\frac{\varepsilon - 1}{\varepsilon + 2}\right)$$

Which also has the same inverse $\varepsilon + 2$ dependence and gets enhanced at $n_e = 3n_c$. In a practical situation, ε depends on collision frequency also and the expression gets modified to:

$$\varepsilon = 1 - \omega_p^2/(\omega_l(\omega_l + i\nu))$$

Which gives the absorption a finite width and finite peak, instead of being a Dirac delta function.

Coulomb Explosion

When the resonance condition is reached in a cluster, the field inside becomes extremely high due to field enhancement. This filed gives a high amplitude of oscillation to the electron, driving it out of the cluster. Once the electron is out of the cluster, it sees the actual electric field of the Laser which is much lower than the inside field.

As a result, the electrons which come out of the cluster tend to fly off (as the field outside is too low to push them back into the cluster), leaving a cluster of positively charged ions. Due to the strong Coulomb repulsion, this cluster expands with a high velocity (i.e. explodes). This phenomenon is called Coulomb Explosion.

Fusion neutron generation by cluster explosion

Coulomb explosion has been used to produce fusion neutrons from deuterium clusters. As deuterium does not cluster at room temperature, deuterium gas is first cooled to liquid nitrogen temperature and then puffed out to get deuterium clusters. These clusters when irradiated by Laser, explode into high energy deuterium ions. The deuterium ions from different clusters collide against each other and produce neutrons by the following fusion reaction.

$$D + D \rightarrow He3 + n \ (2.45 \text{ MeV})$$

105 neutrons per joule of Laser energy have been observed.

References

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