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Linear Absorption Mechanisms in Laser Plasma Interactions

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Abstract: In this study, we investigated some effective parameters related to the plasma and the laser characteristics on linear absorption mechanisms such as; plasma scale length, plasma density profile, laser intensity and laser pulse duration. We classify different approaches which lead to different solutions for the wave equation in plasma medium. We showed that, there are some restrictions with applying the linear theory in absorption. Finally we pointed out that there are some restrictions to apply linear theory in absorption. We will see in which regimes collisional or resonance absorption is dominant.

Key words: Plasma density profile, plasma scale length, collisional absorption, resonance absorption, laser pulse duration

INTRODUCTION

One of the main absorption mechanisms in laser plasma interactions is linear absorption, especially in regimes where some important rival absorption mechanisms such as vacuum heating and parametric absorption are less significant. There are many parameters which are important in determining the absorption from laser to the plasma. The characteristics related to the plasma such as density profile and scale length and also, the characteristics related to the laser such as intensity, pulse duration and shape of pulse are the main parameters which affect on absorption process. On the other hand, the computational approach to solve equations may produce an approximate or accurate solution such as WKB approximation in plasma large scale length or Fresnel equations in step function or very steepen density profile which both present an excellent approximation, but the numerical method yields still better results in every regime (Gibbon, 2005). When a laser light incidents on plasma, some part of it may be reflected in vacuum-plasma borderline and it also will be reflected classically in a certain point of plasma which is named as turning point. However, this turning point is less than distance which the laser light actually can reach in plasma depth due to quantum mechanical tunneling effect. Laser light doesn't penetrate into the plasma more than critical surface due to resonance absorption and the large amplitude plasma wave (Langmuir) will be excited. In collisional absorption, laser beam interact with electrons and gradually become damped (Cai *et al*., 2006; Nazarenko *et al*., 1995). In addition to the reflection, laser light suffers from the other important phenomena such as; scattering or dissipation. In high intensity, some nonlinear phenomena such as self focusing rivals with dissipation and laser light will not be much diverged. We can drive a suitable form of electric and magnetic parts of the laser light (and plasma electrostatic field) in plasma with the coupling of Maxwell's equations as for laser light and plasma wave equations (in resonance absorption) or electron fluid equations (in collisional absorption) (Kruer, 1978). Basically, the linearization of these equations presents a good approximation which displays the main features of laser-plasma interaction. With the indication of some agents which lead to nonlinear behavior of quantities such as; plasma density profile deformation due to Ponderomotive force, or variation of laser propagational characteristics such as self-focusing occurrence, some modification should be considered (Bauer and Mulser, 2007).

COLLISIONAL ABSORPTION

Theoretical approach in collisional absorption: In collisional absorption, laser energy is transferred to the plasma electrons and then through columbic interactions (mostly in electron-ion collisions), this transferred energy redistributes on lattice and heats the plasma locally (Pfalzner, 2006). This process occurs in nonuniform density profile and decreases with increasing laser intensity in which for high laser intensities:

$$\left(I > 10^{15}\,\frac{W}{cm^2}\right)$$

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the collisions become less effective (Atzeni and Meyer-ter-Vehn, 2009). The propagation of the laser electromagnetic field through the plasma, with the coupling of Maxwell's equations related to laser and electron fluid equation, is described by the Helmholtz wave equations as (Albritton and Koch, 1975):

$$\nabla^2\vec{E} - \frac{1}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = \mu_0\frac{\partial\vec{J}}{\partial t} + \vec{\nabla}\left(\vec{\nabla}.\vec{E}\right) \quad (1)$$

$$\nabla^2\vec{B} - \frac{1}{C^2}\frac{\partial^2\vec{E}}{\partial t^2} = \mu_0\vec{\nabla}\times\vec{J} \quad (2)$$

where, $\vec{J} = \sigma\vec{E}$ and:

$$\sigma = i\varepsilon_0\frac{\omega p^2}{\omega L + i\nu_{ei}}$$

is the plasma complex conductivity. By solving the wave equation for an electromagnetic, planar wave propagating through plasma of conductivity σ one gets the linear dispersion relation with the collision (Pfalzner, 2006):

$$k^2 = \frac{\omega_L^{\ 2}}{c^2}\left(1 - \frac{\omega_p^{\ 2}}{\omega_L^{\ 2}} - \frac{i\nu_{ei}\omega_p^{\ 2}}{\omega_L^{\ 3}}\right) \quad (3)$$

where, ω_p and ω_L are the plasma electronic frequency and the laser frequency respectively. ν_{ei} is the electronion collisional frequency. In the plasma corona, the collision frequency is much smaller than the laser frequency, $\nu_{ei} \ll \omega_L$. Collisional (inverse bremsstrahlung) absorption leads to an energy damping as the laser propagates through the plasma. This can be described by the absorption coefficient k_{ib} which is given as twice the imaginary part of "k" after applying Taylor expansion for the root of Eq. 3 in conditions:

$$\nu_{ei} \ll \omega_L, \omega_L^{\ 2} - \omega_p^{\ 2} \gg \frac{\nu_{ei}}{\omega_L}$$

Using the definition of the plasma density profile in critical surface, n_c and substituting:

$$\left(\frac{\omega_p^{\ 2}}{\omega_L^{\ 2}}\right)^2 = \frac{n_e}{n_c}$$

one obtains:

$$k_{ib} = \frac{\nu_{ei}}{c}\frac{n_e^{\ 2}}{n_c^{\ 2}}\left(1 - \frac{n_e}{n_c}\right)^{-1/2} \quad (4)$$

The electron ion collisional frequency in critical surface is defined by Atzeni and Meyer-ter-Vehn (2009):

$$\nu_{ei} = \frac{1}{\tau_{ei}} = \frac{4\sqrt{2\pi}}{3}\frac{n_e Z_i e^4 \mathrm{Ln}\Lambda_e}{m_e^{\ 1/2}\left(K_B T_e\right)^{3/2}} \quad (5)$$

where, n_e, T_e and m_e are plasma density profile, electron temperature and electron mass respectively. Z_i is plasma ion charge, $\mathrm{Ln}\Lambda_e$ is coulomb logarithm and K_B is Boltzmann constant. The dependence of K_{ib} on $\frac{n_e}{n_c}$ reflects the fact that a large fraction of the inverse bremsstrahlung absorption occurs near the critical density. Figure 1 shows collisional absorption coefficient for two different plasma ramp versus laser propagation direction z = 0 is assumed as critical surface. If laser light is absorbed, it means that the laser intensity, I, will change while it is passing through a plasma. If we assume that the laser light moves in z-direction, the actual change of the laser intensity, I, in the plasma is described by:

$$\frac{dI}{dz} = -k_{ib}I \quad (6)$$

In homogeneous plasma, for laser pulses of 1 ns duration or longer with intermediate intensities:

$$\left(I < 10^{14}\frac{w}{cm^2}\right)$$

the electron temperature and coulomb logarithm can be assumed constant (therefore, K_{ib}, is assumed constant). In this situation Eq. 6 without complexity can be solved analytically. The absorption coefficient over length L is related to the difference between the incoming I_{in} and outgoing I_{out} laser intensity, which is given by:

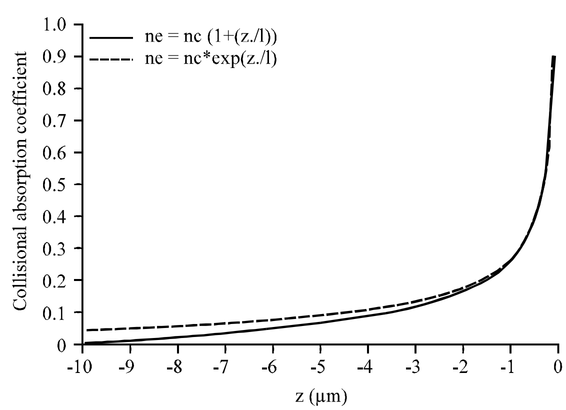

Fig. 1: Collisional absorption coefficient versus z-coordinate

$$A_{ib} = \frac{I_{in} - I_{out}}{I_{in}} = 1 - \exp\left(-\int_0^L k_{ib}\,dz\right) \quad (7)$$

The numerical solution of Helmholtz's equations yields the absorption fraction of laser light due to collisional absorption.

Collisional absorption fraction and plasma density profile in different cases: The energy transported by the electromagnetic field $\vec{B}(t)$ and $\vec{E}(t)$ while it propagating through a dielectric medium with a refractive index, n, can be characterized by plasma and laser parameters such as plasma scale length and laser wavelength. There are different cases according to $\frac{L}{\lambda}=0$ ratio, where L and λ are plasma scale length and laser wavelength respectively:

(1) $\frac{L}{\lambda}\approx 0$ This is referred to as step function profile (Vacuum-homogeneous plasma interface condition). The Fresnel coefficients determine the fraction of reflected and transmitted (and absorbed) light in the plasma medium , these coefficients are determined through by solving the wave equation across the media interface for "P" and "S" components of the radiation independently (Gibbon, 2005). Figure 2 and 3 show the curves of transmitted, reflected and absorption fraction of laser versus the angle of incident in "P" and "S" polarization for Vacuum-homogeneous plasma interface

(2) Slowly varying profile, $\frac{L}{\lambda}\gg 1$. We can apply WKB approximation. By applying WKB approximation method (Albritton and Koch, 1975), for a linear density profile of the form $n_e = n_c(1\text{-}z/L)$, Ginzburg showed that the analytical answer of the absorption coefficient is given by Pfalzner (2006):

$$A_{ib} = 1 - \exp\left[-\frac{32}{5}\frac{\nu_{ei}(n_c)^L}{c}\right] \quad (8)$$

and Kruer (1987) also showed for an exponential profile of the form $n_e = n_c \exp(z/L)$ coefficient is given by:

$$A_{ib} = 1 - \exp\left[-\frac{8}{3}\frac{\nu_{ei}(n_c)L}{c}\right] \quad (9)$$

and laser intensity dependence of fractional absorption is given by (Atzeni and Meyer-ter-Vehn, 2009):

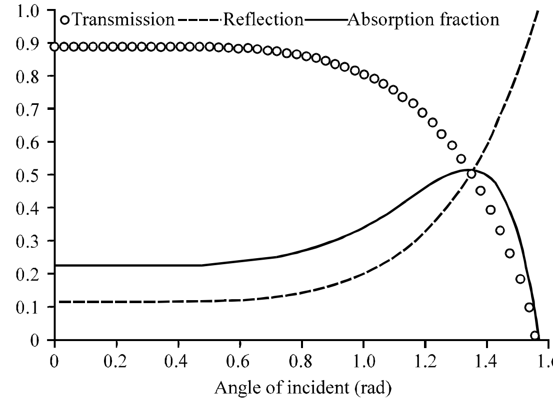

Fig. 2: Transmitted and reflected part and absorption fraction of laser versus the incident angle according to Fresnel equations in p-polarization

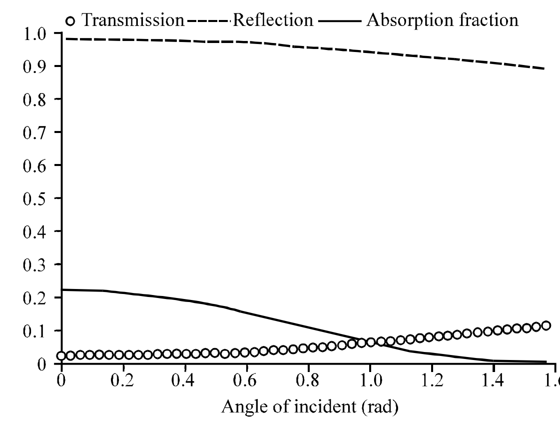

Fig. 3: Transmitted and reflected part and absorption fraction of laser versus the incident angle according to Fresnel equations in s-polarization

$$A_{ib} = 1 - \exp\left[-\frac{I_L^*}{A_{ib} I_L}\right] \quad (10)$$

Where:

$$I_L^* = 1.5\times 10^{11}\frac{Z_i fL}{\lambda^4}\left(\text{w cm}^{-2}\right) \quad (11)$$

Factor f accounts for flux inhibition and Z_i, is ion charge. The total fractional absorption is depended on plasma scale length, laser wavelength and plasma temperature and laser intensity. These can be described in Fig. 4-7. Figure 4 shows the total fractional absorption versus plasma scale length for two different forms of plasma profile. It is shown that the total fractional absorption increases with increasing the plasma scale length. The variation of total fractional absorption versus laser wavelength,

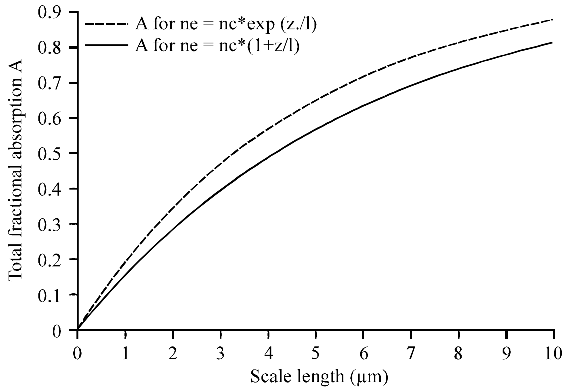

Fig. 4: Total fractional absorption versus plasma scale length

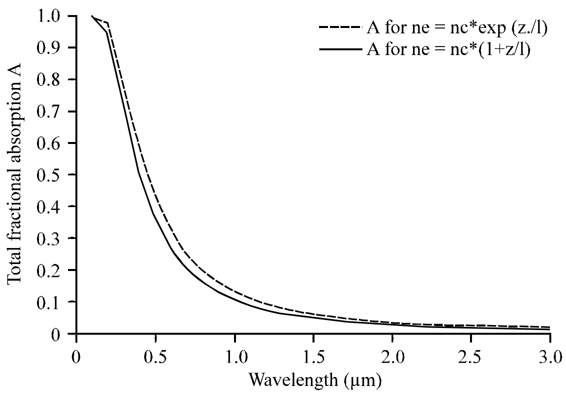

Fig. 5: Total fractional absorption versus laser wavelength

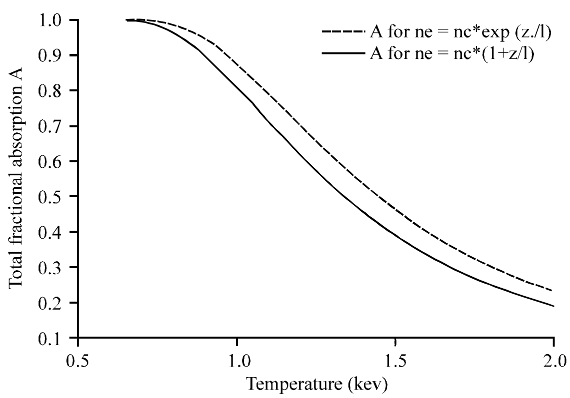

Fig. 6: Total fractional absorption versus plasma temperature

plasma temperature and laser intensity is shown in Fig. 5-7. That the total fractional absorption in collisional absorption decreases with the increase of laser wavelength, plasma temperature and laser intensity because the number of collisions decreases in temperature T_e>1 KeV and laser intensity I_L>10^{15}(W cm^{-2}).

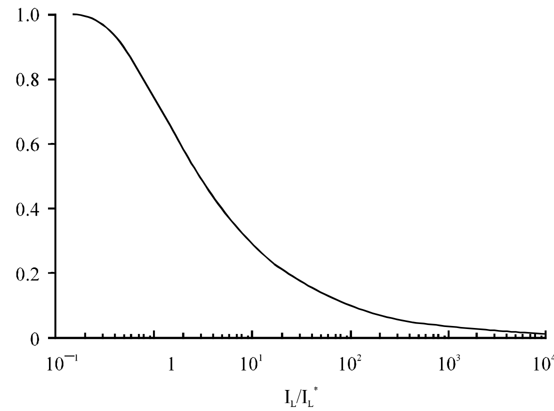

Fig. 7: Total fractional absorption versus normalized intensity

(3) For steepen profile, $\frac{L}{\lambda} << 1$, numerical solutions yields the absorption fraction. The numerical solution of the wave equations for collisional absorption in steep plasma gradients is similar to resonance absorption .

RESONANCE ABSORPTION

Theoretical approach in resonance absorption: One of the coupling modes in laser plasma interaction is the one related to the collective behavior of plasma. When a P-polarized light has a component of electric field in laser direction, laser beam deposits its energy non-locally in plasma and plasma wave is excited in the critical layer $\omega_p = \omega_L$ (Pfalzner, 2006). This mechanism is called resonance absorption. After excitation of large amplitude plasma wave in the critical surface, this wave will be damped at short time (a time less than wave breaking time) through collisional mechanisms (i-e., collisions), or collisionless collective effects (i.e., Landau damping) and wave breaking phenomena. The result of these phenomena is plasma heating and at the consequence hot electrons would be produced. For the high intensity laser, there is a nonlinear important phenomenon which is named wave breaking that pulls out the electrons from the wave and as a result, the wave begins to decay with the time (Albritton and Koch, 1975):

$$\tau_\omega \approx \left(\frac{Lm_e}{eE_z}\right)^{1/2} \tag{12}$$

This is an estimation of the wave breaking time. Decreasing E_z leads to increasing τ_ω and the wave stands for a longer time therefore, the decay time increases.

The wave differential equations in plasma in resonance absorption state can be obtained through coupling of Maxwell's equations and the plasma electrostatic wave as follow (Cai *et al*., 2006; Kruer, 1987):

$$\frac{d^2B_y(z)}{dz^2}-\frac{1d\varepsilon_1}{\varepsilon_1 dz}\frac{dB_y(z)}{dz}+k_0\left(\varepsilon_1-\sin^2\theta o\right)B_y(z)=0 \quad (13)$$

where, k_0, ε_1 and θ_0 are laser wave number in vacuum , plasma dielectric function and the incident angle of laser relative to normal of plasma target, respectively. This differential equation may be solved analytically only in certain regimes but the numerical solution is possible for all regimes. The electric field in plasma can be rewritten to two distinct fields: $E_z = E_{zL}+E_{zP}$. The first term is related to the laser and the later is the plasma electrostatic field:

$$E_z=-\frac{1}{c}\frac{\partial A_z}{\partial t}-\frac{\partial\varphi}{\partial z} \quad (14)$$

where, A_z is the vector potential and φ is the scalar potential. Starting with $\vec{B}=\vec{\nabla}\times\vec{A},\vec{\nabla}.\vec{A}=0$ and:

$$E_{ZL}=\frac{1}{c}\frac{\partial A_z}{\partial t}$$

we obtain:

$$\frac{d^2E_{zL}(z)}{dz^2}-k_0{}^2\left(\sin^2\theta_0\right)E_{zL}(z)=-k_0{}^2\left(\sin^2\theta_0\right)B_y(z)\ \vec{\nabla}.\vec{A}=0 \quad (15)$$

with considering $B_y(z)$which is given by Eq. 13, together with the boundary conditions, E_{zL} can be solved from Eq. 15. By using the Ampere's law, we have:

$$E_z=\sin\theta_0\frac{B_y}{\varepsilon_1(z)}$$

and then we can obtain E_{zp} which we need to calculate the absorption fraction. Therefore, we obtain the absorption rate *f*RA due to the damping of the plasma wave E_{zp} as following:

$$f_{RA}=\frac{\nu}{8\pi I_L}\int_{-\infty}^{+\infty}|E_Zp|^2\,dz \quad (16)$$

Where:

$$I_L=\frac{cE^2}{8\pi}$$

is the incident power. Because the height of the resonance is proportional to ν and the width of the resonance is proportional to 1/ν, then, Eq. 16 is not dependant on ν.

On the other hand, when a laser light propagates into the plasma, it reflects classically in turning point, but due to QM tunneling effect, the wave still goes ahead and finally in critical surface will be absorbed almost completely . The turning point is determined as follows (Atzeni and Meyer-ter-Vehn, 2009; Kruer, 1987):

$$n_e=n_c\cos^2\theta \quad (17)$$

for density profile $n_e = n_c(1\text{-}z/L)$, we have:

$$n_e=n_c\left(1-z/L\right)=n_c\cos^2\theta \quad (18)$$

then, turning point, z and the tunneling distance Δz are determined as:

$$z=L\sin^2\theta \qquad \Delta z=L-L\sin^2\theta=\cos^2\theta \quad (19)$$

Figure 8 shows the turning point and tunneling distance versus the angle of incident. The tunneling distance decreases with increasing the incident angle but turning point increases with increasing the incident angle. In addition, absorption power peak which describes the optimum angle to maximum efficiency, is considered at $\theta=\frac{\pi}{4}$ we should notice that there is no absorption in angle zero and $\frac{\pi}{2}$ because , in the angle zero, the tunneling distance is long and in the angle $\frac{\pi}{2}$, physically, there is no z-component of laser in plasma ramp. For cold Plasma, the dielectric function is:

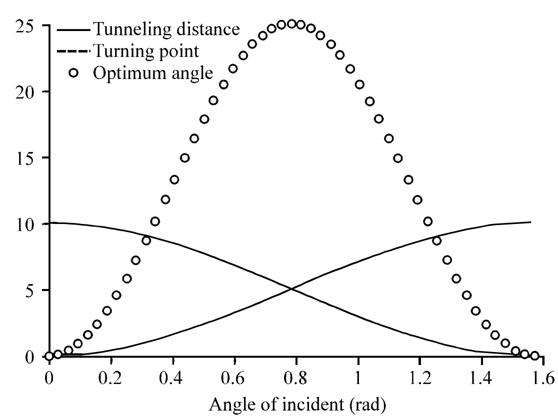

Fig. 8: Dependence of tunneling distance, turning point and absorption power versus the incident angle to find the optimum angle of absorption power (Vertical axes in arbitrary unit)

$$\varepsilon_1(z) \approx 1-\omega_p^2(z)/\omega_o^2\left(1+i\frac{\nu}{\omega_o}\right)$$

Where:

$$\omega_p^2 = \left(\frac{4\pi n_e(z)e^z}{m_e}\right)^{1/2}$$

is the electron plasma frequency. The term of $\frac{\nu}{\omega_o}$ is related to collisional damping. ω_0 and ν are laser frequency and a small effective damping rate:

$$\left(\frac{\nu}{\omega_o} << 1\right)$$

respectively. If we have plasma medium with space inhomogeneity in density profile, then $\varepsilon_1(z)$ will have a gradient form and there is a damping term in the differential equation of laser magnetic field (second term in Eq. 13). Consequently, the wave will deposit its energy in plasma medium.

Plasma density profile: The laser magnetic field doesn't experience any change in constant density profile purely due to resonance absorption without considering the other interaction mechanisms, therefore laser light passes across the plasma without energy deposition.

In ICF, plasma is divided to Underdense and Overdense regions. If laser doesn't deposit its energy in underdense region, it cannot also approximately deposit its energy in overdense region, because this later is very steepen and practically we can assume it , in constant profile situation. So the constant profile density in underdense region can not lead to resonance absorption. Figure 9 shows the magnetic field of laser without any loosing amplitude while it is passing across the collisionless plasma. According to Eq. 13, we can see with being a gradient form for dielectric function of plasma, there is a damping term for magnetic (and electric) wave. As a result, the laser light will deposit its energy into the plasma medium. On the other hand, a gradient for dielectric function is possible with considering a gradient for plasma density. The resonance absorption will change with considering different formats of plasma ramp. Basically, the plasma scale length:

$$L = \left(\frac{\partial \ln n_e}{\partial z}\right)^{-1}$$

and laser wavelength are parameters which determine the situation of plasma in our computational approach as follows:

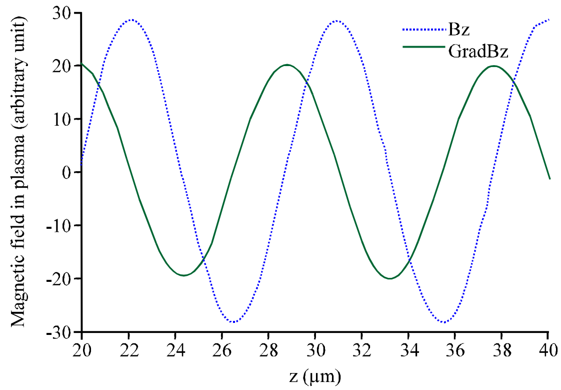

Fig. 9: Laser magnetic field in plasma with constant density profile versus z coordinate

(1) If $\frac{L}{\lambda} \approx 0$, the profile is step function, the Fresnel equations determine the absorption in plasma medium and the resonance absorption doesn't occur.
(2) If $\frac{L}{\lambda} >> 1$, the profile has a long slowly varying form and WKB approximation is valid. In the limit of the WKB approximation for a linear density profile, the absorption fraction is:

$$f_{RA} \approx \varphi^2(\tau)/2$$

Where:

$$\varphi(\tau) \approx 2.3\tau \exp\left(-\frac{2\tau^2}{3}\right)$$

and $\tau = (KL)^{1/3}\sin\theta$ (that is the Ginzburg classical function). Figure 10 shows the square of plasma electrostatic field versus the incident angle of laser by WKB approximation. It is shown that the maximum of plasma electrostatic field takes place in optimum angle $\theta = \frac{\pi}{4}$ for $KL>10$. The main consequences of the angular absorption behavior can be summarized as follows:

(i) At angles close to $\pi/2$, the laser field has no component along the plasma gradient and the resonant energy transfer doesn't take place in plasma. Figure 10 also shows that the maximum of plasma electrostatic field for $KL<1$ takes place in angle $\theta = \frac{\pi}{2}$. This is unacceptable result because there is no z-component of laser driver in angle $\theta = \frac{\pi}{2}$.

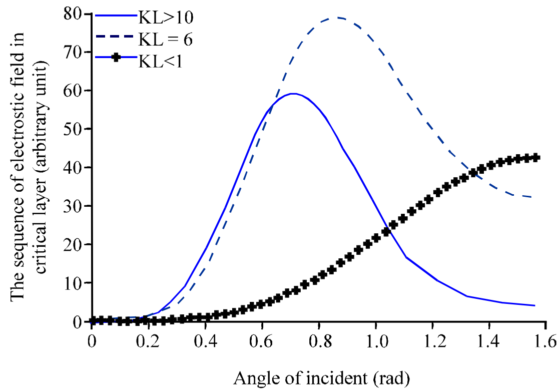

Fig. 10: Square of plasma electrostatic field versus the incident angle of laser

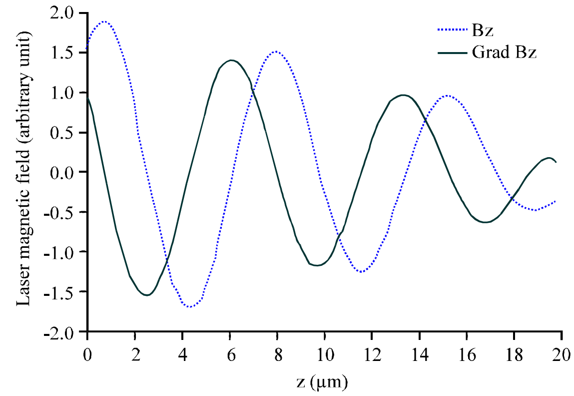

Fig. 12: Magnetic field of laser versus z coordinate

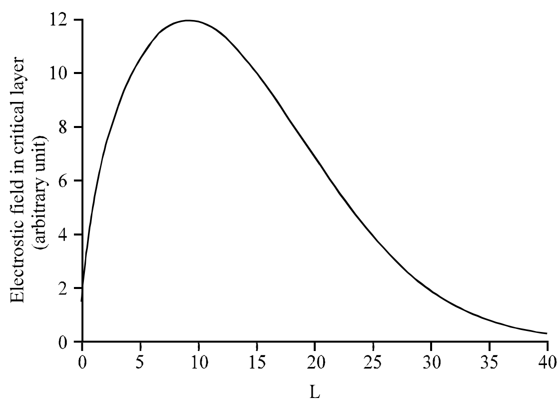

Fig. 11: Electrostatic field in critical surface versus different plasma scale length

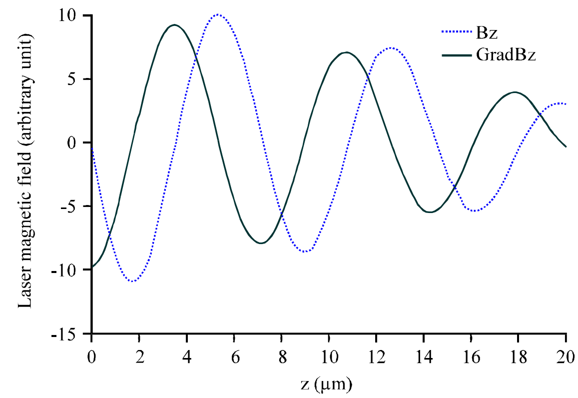

Fig. 13: Electric field of laser versus z coordinate

(ii) At angles close to 0, the parallel component of the laser field must be tunnel through a very long distance up to the critical point then, the driver field becomes very small, therefore the electrostatic field is almost zero (Fig. 10).

(iii) The optimum absorption angle is for $\theta=\frac{\pi}{4}$ for KL>10, because the Ginzburg function is estimated as 0.5. The optimum angle is shifted towards higher incidence angle in steeper plasma profiles for KL≤1 if we assume still WKB approximation. But in the next section, we will see from numerical calculation that in smaller scale length, the optimum angle is again $\theta=\frac{\pi}{4}$.

The optimum angle is actually the angle which the square electrostatic field is maximized. Figure 11 shows the electrostatic field versus plasma scale length in critical surface according to WKB approximation. The resonance absorption is very low in very small and large scale length. In plasma with large scale length, the magnetic (or electric) field of laser becomes more damped and the driver field fails. But in very small scale length, the WKB approach doesn't give a correct answer and to present a correct behavior of the wave, we need to solve the problem numerically.

(3) If $\frac{L}{\lambda}$<<1 the profile is sharp or steepen and the WKB approximation is no longer valid, but the problem can be solved numerically. In Fig. (12-15), we obtained the variation of magnetic and electric field of laser and plasma versus z-coordinates numerically for K_L<0.5. We can conclude from the Fig. (12-15), the excitation of plasma electrostatic field occurs due to damping of electric field of laser. At this case underdense plasma behavior is actually similar to overdense plasma and strikingly is collisional. It should be noticed that considering energy coupling in linear mode is not valid as long as the resonance width (which is proportional with collisional frequency) becomes larger than plasma profile (Yang *et al*., 1996).

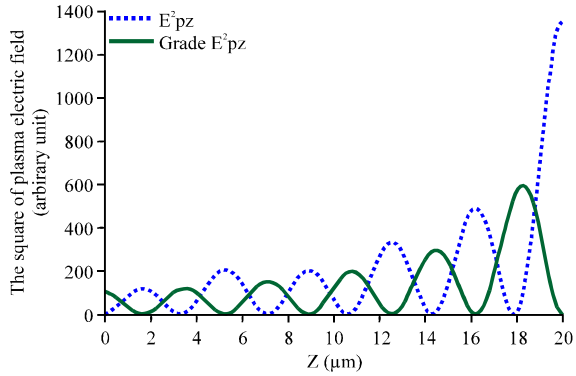

Fig. 14: Plasma electrostatic field versus z coordinate

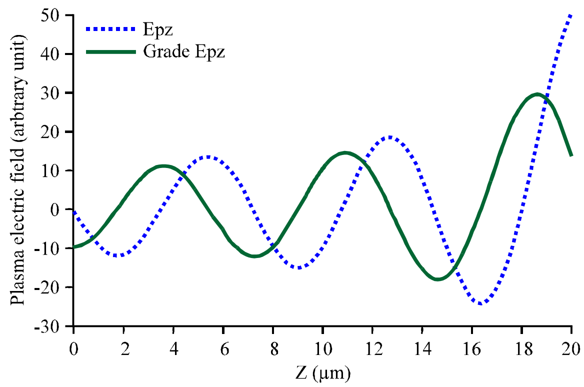

Fig. 15: Square of plasma electrostatic field versus z coordinate

Pulse duration effect in resonance absorption: For a monochromatic laser field in limit $\frac{L}{\lambda} >> 1$, at an angle θ with the amplitude $E_{0\omega}$ the plasma electrostatic field can be written as (Nazarenko *et al*., 1995):

$$E_{zp} = \frac{i \sin\theta E_{0\omega} \Lambda \exp(-i\omega_0 t)}{z/1 - 1 + \omega p^2/\omega_0^2 + i\nu/\omega_0} \quad (20)$$

where, ν is the frequency of electron collisions and L is the plasma density scale length. The factor Λ is proportional to the magnetic field amplitude of the incident wave at the resonant point and describes the tunneling of the electromagnetic wave to the resonant point and it can be expressed in terms of Airy functions (Gibbon, 2005). A reasonably good approximation (Cai *et al*., 2006; Zhang *et al*., 2005) is given by:

$$\Lambda(q) = 2.3\sqrt{q}\exp\left(-\frac{2}{3}q^2\right)$$

where, $q = (KL)^{2/3}\sin^2\theta$, $k = \omega_0/c$. Figure 16 shows the electric field in plasma in limit $KL \geq 10$ at time $t = 0$, (critical surface is located at $z = 0$). It is shown that the resonance height is lower in very large scale length of plasma. For a Gaussian signal in long pulse limit we can obtain (Nazarenko *et al*., 1995):

$$E_{zp} = \frac{i \sin\theta \exp\left(-t^2/2\tau^2 - i\omega_0 t\right)}{z/L + i\nu/\omega_0} \quad (21)$$

In Eq. 21, τ is indicated as pulse duration. We consider two opposite cases; (A) Long pulse limit $\nu\tau >> 1$ and B) Short pulse limit $\nu\tau << 1$. The behavior of the electrostatic field in these two cases is somewhat different. In long pulse limit, we have maximum value of the electric field:

$$E_{zp} - \max = \frac{E_0\omega_0}{\nu}$$

with the width of the electric field peak:

$$\Delta z \approx \frac{L\nu}{\omega_0}$$

but in short pulse limit, we have maximum value of the electric field, E_{zp}-max = $E_0\omega_0\,\tau$ with the width of the electric field peak:

$$\Delta z \approx \frac{L\nu}{\omega_0}.$$

In short pulse limit, with increasing pulse duration, the width of peak becomes narrower and the height of peak increases. Also in long pulse limit, more collisionality leads to an increase in the height of peak and the width of peak increases with the increase in the plasma scale length and collisionality both.

Nonlinearity restrictions: Nonlinearity restrictions may be created in three cases:

- In nonlinear optics conditions (which usually occur in high intensity).
- In nonlinear plasma wave conditions, for example; deformed plasma density profile which is due to the strong Ponderomotive force (in high intensity), the wave breaking (in long pulse limit)or second harmonic generation (in shortening pulse duration). There is a criterion in applying linear limit at resonance absorption for the long pulse case as follows (Yang *et al*., 1996):

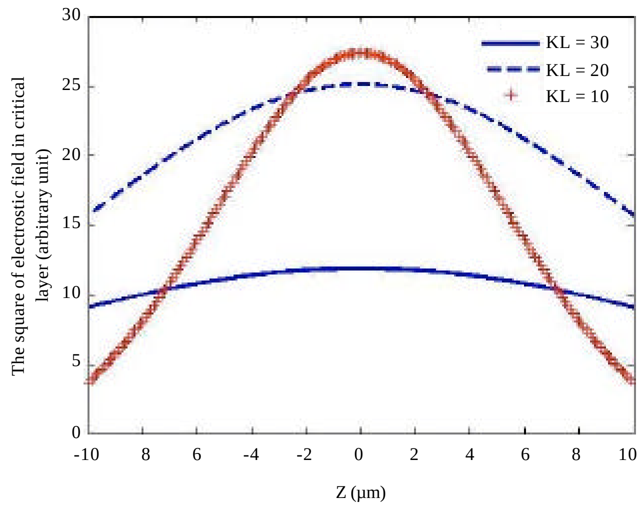

Fig. 16: Square of electric field in critical layer in kL >> 1 limit for monochromatic laser

$$\frac{\delta n}{n} \approx \frac{E_0^2}{8\pi nT}\frac{\omega_0^2}{v^2} < \frac{\Delta z}{L} \approx \frac{v}{\omega_0} \tag{22}$$

For short pulse limit we have (Yang *et al*., 1996):

$$\frac{\delta n}{n} \approx \frac{E_0^2}{16\pi nT}\left(\omega_0^2\tau\right)^4 \frac{\tau^2 c_s^2}{L^2} \tag{23}$$

Where Cs, T and n are the speed of sound, laser period and plasma density respectively.
Wave breaking can occur faster than the nonlinear profile deformation in high intensity by the irradiative force. If the pulse duration τ is smaller than T, the linear theory can be used for the description of the resonant absorption process.

- When there are nonlinear terms (higher orders) in the coupling of Maxwell equations and Plasma waves.

CONCLUSIONS

P-polarized laser light produces the fast electrons in laser propagation direction for collisional absorption and it excites the longitudinal plasma wave in resonance absorption. The Resonance absorption can dominate over inverse Bremsstrahlung absorption for high plasma temperatures and low critical densities. But the collisional absorption is the dominant absorption mechanism in long plasma scale length and cold plasma in intensity:

$$I < 10^{15}\left(\frac{w}{cm^2}\right)$$

An analytical solution exists for differential equation of laser electromagnetic fields in scale length: $\frac{L}{\lambda}=0$ and $\frac{L}{\lambda}>>1$ but for: $\frac{L}{\lambda}=<<1$ numerical solution exists.
It is shown that the pulse duration can change the structure of resonance peak and the shortening of pulse leads to increase the width of peak and decreasing the height of peak, but the collisionality increases and the scale length leads to an increase in the width of peak and a decreases the height of peak in short pulse limit. Pulse shortening leads to nonlinearity restrictions such as; producing second harmonic generation and plasma density profile deformation. In this case, we should modify linear absorption mechanisms. Wave breaking is also an important phenomenon in short pulse limit especially in long scale length which leads to nonlinearity restrictions.

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