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Inverse Braking Radiation and Resonance Absorption in Corona Plasmas of Inertial Confinement Fusion

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Abstract: In this paper, combining the Maxwell equations with the electron balance equation, we obtain the inverse braking radiation absorption coefficient in a laser fusion corona plasma. For a fixed plasma temperature, variations of the absorption coefficient versus the penetration depth into the plasma are illustrated numerically for different values of laser wavelength. It is shown that, by increasing the skin depth of the laser into the plasma, the absorption coefficient increases and tends to asymptotic value one. The effect of plasma temperature on the absorption coefficient has also been investigated. In addition, the fraction of absorbed energy for resonance absorption is studied analytically and illustrated numerically. Moreover, the fractional absorption for different laser wavelengths as well as different values of incident angle is illustrated. It can be seen that, the maximum value of the absorption coefficient is independent of the laser wavelength and is about 0.6 for all the wavelengths.

Keywords: Bremsstrahlung, Corona Plasma, Resonance Absorption, Laser Fusion

1. INTRODUCTION

Increasing laser energy absorption through inertial confinement fusion is one of the main aims in laser- plasma interactions studies. In direct-drive inertial confinement fusion, a fuel pellet consisting of small capsules of deuterium-tritium are irradiated by a limited number of beams [1-12]. At early times, laser light is absorbed by the target, leading to the ablation of target material to form a hot plasma. The laser irradiation typically starts with a sequence of one to three low-intensity pulses, sometimes known as “pickets.”

To begin the energy absorption step, the corona plasma is formed by surface evaporation [5, 13]. The plasma produced by laser interaction with solid matter

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has inhomogeneous density profile. By irradiating the plasma with laser, provided that the electric field has a component along the direction of plasma density gradient, the plasma electrostatic waves will be excited. The electric field near the critical surface becomes very large. In this case, the waves so-called excited resonantly [14-16]. So, in laser–plasma interaction, the critical surface plays a very important role; part of the laser beam is absorbed there and the other part is reflected from this surface. The energy of the electromagnetic wave is transmitted to the plasma waves in such a way that the laser waves damped. The transfer of energy from the laser beam to the plasma through stimulation of the waves is called resonance absorption.

The radiation emitted by a charged particle during the collision with another particle is customarily called bremsstrahlung (in German 'braking radiation') because it was first detected when high-energy electrons were stopped in a thick metallic target [17-19]. In the bremsstrahlung effect a free electron collides with ions and emits a photon [18].

Electron-ion collision created by a laser has two important effects on the plasma. The first is the absorption of photon energy through bremsstrahlung radiation and the second effect is the plasma heating.

Collisional or inverse bremsstrahlung absorption is an essential mechanism for coupling laser energy to the plasma. Inverse bremsstrahlung damping is the process that converts the coherent movement of the electrons in the wave into thermal energy. For densities larger than the critical density (n_c), the wave cannot propagate. Laser light is absorbed near the critical surface via inverse bremsstrahlung the following way: The electrical field induced by the laser the causes electrons in the plasma to oscillate. This oscillation energy is converted into thermal energy via electron-ion collisions, a process known as inverse bremsstrahlung [2]. Note that the resonance absorption process is independent of the details of the damping process. This means that, in contrast to inverse bremsstrahlung, resonance absorption can be efficient even for very low electron-ion collision frequencies. Therefore, resonance absorption can dominate over inverse bremsstrahlung absorption for high plasma temperatures, low critical densities, and short plasma scale-length. Put another way, resonance absorption is the main absorption process for high laser intensities and long wavelengths.

High-frequency lasers have developed for inertial confinement fusion (ICF). The interaction of high-intensity lasers with plasma without considering relativistic effects is not sense. Here, we study the nonlinear bremsstrahlung absorption with considering the relativistic corrections. Also, the laser resonance absorption in the corona plasma is investigated for inertial confinement fusion and the absorption energy rate is calculated for a high intensity laser beam for various incident angles.

2. INVERSE BREMSSTRAHLUNG

Bremsstrahlung and inverse bremsstrahlung are connected the following way: if two charged particles undergo a coulomb collision they emit radiation, so-called bremsstrahlung $(e+i \to e+i+\gamma)$. Inverse bremsstrahlung is the opposite process, where an electron scattered in the field of an ion absorbs a photon $(e+i+\gamma \to e+i)$. So, Collisional or inverse bremsstrahlung damping is the process that converts the coherent movement of the electrons in the wave into thermal energy. The energy conversion proceeds through electron-ion collisions [2].

By solving the electron equation of motion and Maxwell equations, it can be shown that the rate of laser energy damping caused by bremsstrahlung radiation is obtained by the following equation [2, 17]:

$$\kappa_{\mathrm{ib}} = \left(\frac{\nu_{\mathrm{ei}}(n_{\mathrm{c}})}{c}\right)\left(\frac{n_{\mathrm{e}}}{n_{\mathrm{c}}}\right)^2\left(1-\frac{n_{\mathrm{e}}^2}{n_{\mathrm{c}}^2}\right)^{-1/2} \tag{1}$$

In which, n_{e} is the electron plasma density, c the speed of light in vacuum and $\nu_{\mathrm{ei}}(n_{\mathrm{c}})$ represents the electron-ion collision frequency at critical density $n_{\mathrm{c}} = m_{\mathrm{e}}\omega_{\mathrm{L}}^2 / 4\pi e^2$. Also, m_{e} is the electron rest mass, e the magnitude of the electron charge and ω_{L} is the laser frequency. The subscripts $'ib'$ in the absorption coefficient κ_{ib} refers to the ‘inverse bremsstrahlung’ radiation. Note that the cutoff condition occurs at a critical density n_{c} such that $\omega = \omega_{\mathrm{p}}$ in which ω_{p} is the plasma frequency. The dependence of κ_{ib} on $n_{\mathrm{e}}/n_{\mathrm{c}}$ in equation (1) shows that a significant fraction of the inverse bremsstrahlung absorption is from the region near the critical density, $n_{\mathrm{e}}/n_{\mathrm{c}} \simeq 1$.

On the other hand, the changes in the laser intensity while passing through the plasma in the z direction is described by $\dfrac{dI}{dz} = -\kappa_{\mathrm{ib}} I$.

Now, by solving this differential equation, the absorption coefficient of the bremsstrahlung radiation is determined by [18]

$$\alpha = \frac{I_{\mathrm{in}} - I_{\mathrm{out}}}{I_{\mathrm{in}}} = 1 - \exp\left[-\int_0^L \kappa_{\mathrm{ib}}\, dz\right] \tag{2}$$

where L is the length of the plasma. The incoming and outgoing laser intensities represent by I_{in} and I_{out} respectively. For a plasma with linear density profile $n_{\text{e}} = n_{\text{c}}\left(1 - z/L\right)$, by solving equation (2) one obtain

$$\alpha = 1 - \exp\left[-\frac{16}{15}\frac{\nu_{\text{ei}}(n_{\text{c}})L}{c}\right] \tag{3}$$

Using equation (3), we calculate the inverse bremsstrahlung absorption coefficient for different plasma parameters. Fig. 1 shows the variations of the absorption coefficient with the penetration depth for $T_{\text{e}} = 4keV$ and different values of the critical densities and laser wavelengths. If we recall the conversion factor: $1eV = 11600$, This temperature for plasma with one degree of freedom indicates an energy of $46.4\ MeV$ for particles. In this figure, the blue, red and black curves correspond to wavelength $\lambda = 0.35\mu m$, $\lambda = 0.53\mu m$ and $\lambda = 1.06\mu m$ respectively. For all the wavelength, by increasing the penetration depth of the laser, the absorption coefficient increases and tend to critical value one (100%). At the point that the laser enters the plasma, the exponential term in equation (3) is equal to one and the absorption coefficient is zero. With increasing the laser penetration depth into the plasma, the exponential term decreases and becomes zero. So, the absorption coefficient reaches the asymptotic value one for large penetration depths. The slope of the increase in the inverse bremsstrahlung absorption coefficient decreases with increasing laser wavelength. The sharp increase in the absorption coefficient of the bremsstrahlung radiation is the reason for using short wavelength lasers in inertial confinement fusion.

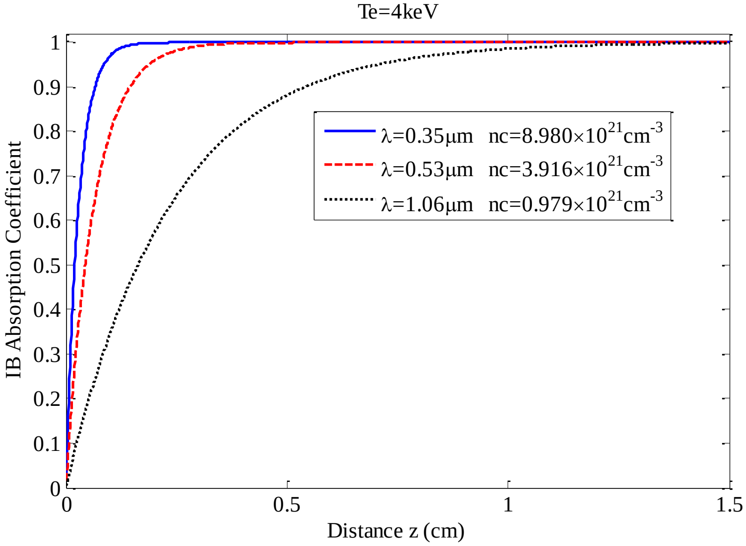

Fig. 1. The absorption coefficient with the penetration depth for T_e =4keV

The relation $n_c = 1.1\times10^{21}\times\left(1\mu m/\lambda_L\right)^2$ is used for calculating the critical number density in which λ_L shows the laser wavelength.

The critical density decreases with increasing the laser wavelength. So, the laser energy damping rate due to the bremsstrahlung radiation grows up and causes the curve slope and the absorption coefficient to increase. In Fig. (2). we raised the plasma temperature up to $T_e = 10keV$ in order to show the role of plasma temperature on the absorption coefficient. Comparing Figures (1) and (2), it is clear that, as the temperature increases, the curves reach the asymptotic value later for all the three wavelengths. The reason for this behavior is related to the dependence of the frequency of collision to the plasma temperature. As the temperature increases, according to the relation below, the collision frequency decreases

$$\nu_{\mathrm{ei}} = \frac{4}{3}\frac{\left(2\pi\right)^{1/2} Z^2 e^4 n_{\mathrm{i}}}{\left(k_{\mathrm{B}}T_{\mathrm{e}}\right)^{3/2} m_{\mathrm{e}}^{1/2}}\ln\Lambda \tag{4}$$

where $\Lambda = b_{\max}/b_{\min}$ and the factor $\ln\Lambda$ is called the Coulomb logarithm, a slowly varying term resulting from the integration over all scattering angles. $b_{\min}$ and $b_{\max}$ show the lower and upper limit for the impact parameter b respectively. Also, Ze and n_{i} represent the charge and density of ions

respectively. The absorption coefficient increases with the decrease of the collision frequency (see (3)).
It is worthwhile to investigate the behavior of the absorption coefficient for different plasma temperatures explicitly. Figure (3) shows the relevant changes. The curves are chosen from figures (1) and (2) for $\lambda = 0.35\mu m$. In this figure, the blue and red curves are related to $T_e = 4keV$ and $T_e = 10keV$ respectively. For $T_e = 4keV$, the inverse bremsstrahlung absorption coefficient reaches the asymptotic value erlier relative to that of $T_e = 10keV$ temperature.

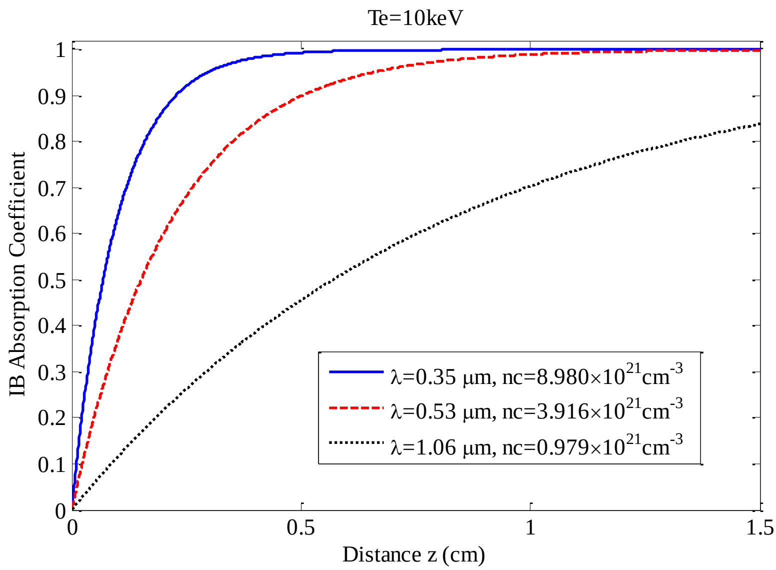

Fig. 2. The absorption coefficient of bremsstrahlung radiation with penetration depth.

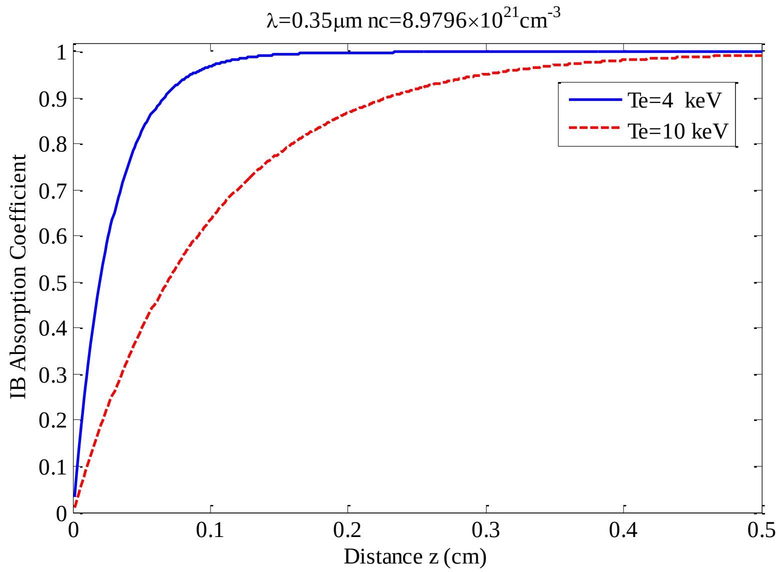

Fig. 3. Comparison of inverse bremsstrahlung absorption coefficient for different plasma temperatures.

For the completeness, we note that at high laser intensities $\left(I > 10^{18}\,W/cm^2\right)$, the electric field component of the laser wave causes the thermal distribution of the electrons to deviate from the Maxwell distribution. In turn, the frequency of the electron's collision with the ions changes. In this case, the absorption coefficient of inverse Bremsstrahlung needs to be modified [21, 22].

3. RESONANCE ABSORPTION

The plasma that is created by the interaction of the laser with a solid target has an inhomogeneous density profile comprising both under- and overdense regions. Whenever light meets a plasma with these characteristics, electrostatic waves are excited if any component of the electric field of the light coincides with the direction of the density gradient (p-polarized interaction). In this case the electric field becomes very large near the critical surface, and it is here that waves are resonantly excited. In this way energy is transferred from the electromagnetic into plasma waves. Because these waves are damped, energy will eventually be converted into thermal energy, thus heating the plasma. This entire process of converting laser energy into plasma heating via wave excitation is called resonance absorption [2]. combining the Maxwell equations, one obtains [18]

$$\nabla^2\mathbf{B}(\mathbf{r})+\left(\frac{\omega^2\varepsilon}{c^2}\right)\mathbf{B}(\mathbf{r})+\left(\frac{\nabla\varepsilon}{\varepsilon}\right)\times\left[\nabla\times\mathbf{B}(\mathbf{r})\right]=0 \tag{5}$$

for the magnetic field component of the wave in the plasma in which $\varepsilon=1-\frac{\omega_{\mathrm{p}}^2}{\omega^2}=1-\frac{n_{\mathrm{e}}}{n_{\mathrm{ec}}}=1-\frac{z}{L}$ is the dielectric constant of the plasma. For the p-polarization obliquely incident laser it is convenient to solve the equation for the magnetic field, which is in the x direction and can be presented by

$$B_{\mathrm{x}}=B(z)\exp\left(\frac{\mathrm{i}\omega y\sin\theta_0}{c}\right) \tag{6}$$

in which θ_0 shows the scattering angle. Now, substituting equations (6) and the definition of the dielectric constant into the wave equation (5) for the magnetic field one has to solve the differential equation

$$\frac{d^2B_{\mathrm{z}}}{dz^2}+\frac{1}{(z-L)}\frac{dB_{\mathrm{z}}}{dz}-\left(\frac{\omega^2}{Lc^2}\right)\left[(z-L)+L\sin^2\theta_0\right]=0 \tag{7}$$

Introducing dimensionless variables $\tau=(\omega L/c)^{1/3}\sin\theta_0$ and $\xi=\left(\omega^2/c^2L\right)^{1/3}(z-L)$, equation (7) takes the form

$$\frac{d^2B_{\mathrm{z}}}{dz^2}-\frac{1}{\xi}\frac{dB}{d\xi}-\left(\xi-\tau^2\right)=0 \tag{8}$$

The differential equation (8) depends on a single parameter τ . This quation is singular at $\xi=0$, i.e. at the critical surface $z=L$. After solving the differential equation (8), we put the magnetic field in the Maxwell equation $\nabla\times\mathbf{B}(r)=-\frac{\mathrm{i}\omega\varepsilon\mathbf{E}(r)}{c}$ and compute the electric field of the wave. The energy flux absorbed by the plasma can be calculated from $I_{\mathrm{abs}}=\int\nu_{\mathrm{eff}}\left(\frac{E^2}{8\pi}\right)dz$. The integral is along the electromagnetic beam path and ν_{eff} is The effective collision frequency. The fraction of the absorbed energy is therefore given by

$$f_{ra}=\frac{I_{abs}}{I_L}=\frac{\int\nu_{\mathrm{eff}}E^2dz}{cE_L^2} \tag{9}$$

For the conditions considered in this section, namely, the linear polarization of the laser beam and linear varying plasma density, the fraction of absorbed energy of a p-polarized wave is [10, 14]

$$f_{\mathrm{ra}} \simeq 36\tau^2 \frac{\left[A_i(\tau)\right]^3}{\left|dA_i(\tau)/d(\tau)\right|} \tag{10}$$

where A_i is the Airy function. Using equation (10), the absorbed laser energy fraction is calculated and for different parameters, the corresponding graphs are illustrated and discussed below. f_{ra} vanishes at $\tau = 0$, goes to zero for $\tau \approx 2$, and has a maximum value at about $\tau \approx 0.8$ with a maximum absorption of about 60%, i.e. $f_{ra}(\tau \approx 0.8) \simeq 0.6$. For perpendicular laser irradiation, the value of τ is zero and therefore the absorption coefficient is zero. In this case, the electric field component of the wave is perpendicular to the plasma density gradient and therefore the resonance absorption is zero as expected. The maximum absorption coefficient is about 0.6. That is, 60% of linear polarized laser energy of type p is absorbed resonantly.

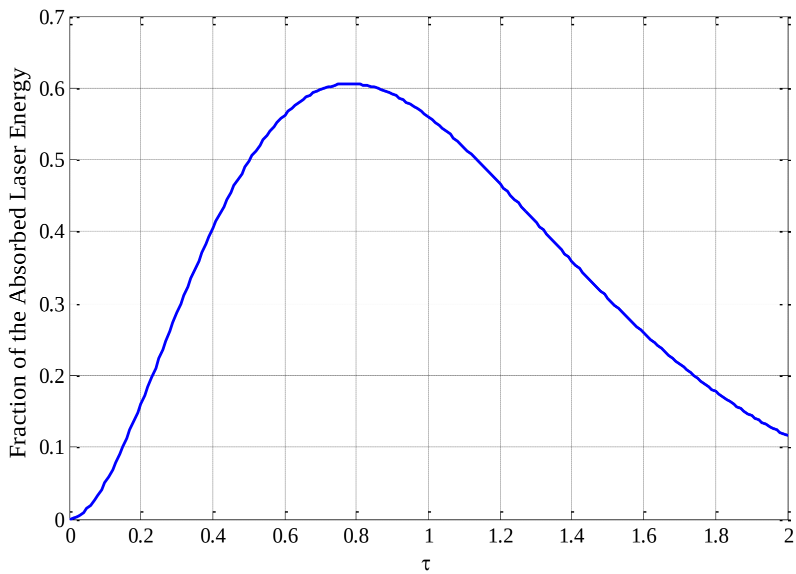

Fig. 4. The fraction of absorbed laser energy

In order to investigate the resonance absorption for different values of laser wavelength, we choose the Neodymium-Glass laser used in the NIF project [8, 20]. Neodymium lasers are the most used laser type in ICF experiments. For three wavelengths, consisting the primary $(\lambda_L = 0.35\mu m)$, the double $(\lambda_L = 0.53\mu m)$ and the triple frequency $(\lambda_L = 1.06\mu m)$, the resonance absorption coefficient of the laser energy is calculated. Plots of f_{ra} are shown in Fig. 5 for different values of incident angles. The scale length is considered $L = 2\mu m$ for all the curves.

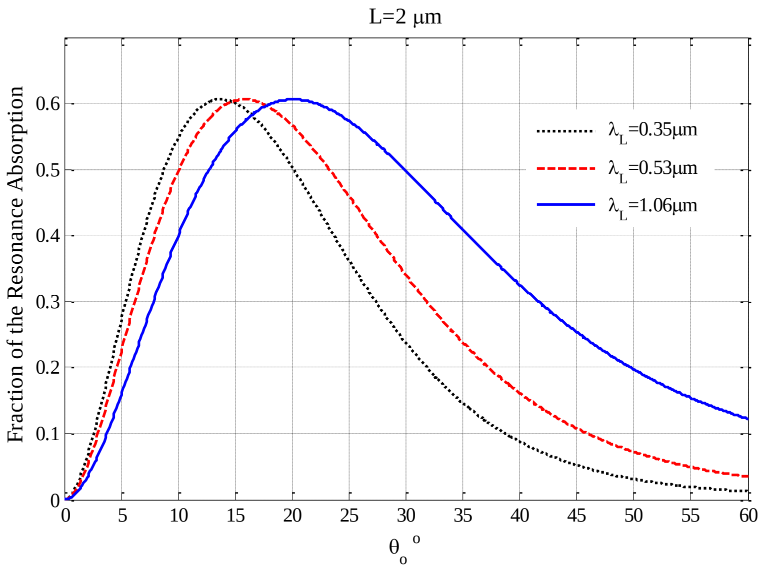

Fig. 5. The fraction of absorbed laser energy versus the incident angles for $L = 2\mu m$

For a light incident with a normal angle of incidence, the resonance absorption coefficient is zero. By increasing the angle of incidence, the absorption coefficient increases and reaching the maximum value. The maximum value of the absorption coefficient is independent of the laser wavelength and is equal to 0.6 for all the three wavelengths. By decreasing the laser wavelength, the peak area of resonance absorption tends to smaller angles. The radiation angle for which the resonance absorption is maximum for the three wavelengths are 20, 15 and 12 degrees respectively. For fusion reaction, it is necessary to absorb the laser energy. So, the laser radiation should be non-perpendicular. On the other hand, the symmetric irradiation of the laser on the fuel pellet is one of the basic principles of inertial confinement fusion. The results show that using short laser can solve these two problems to some extent.

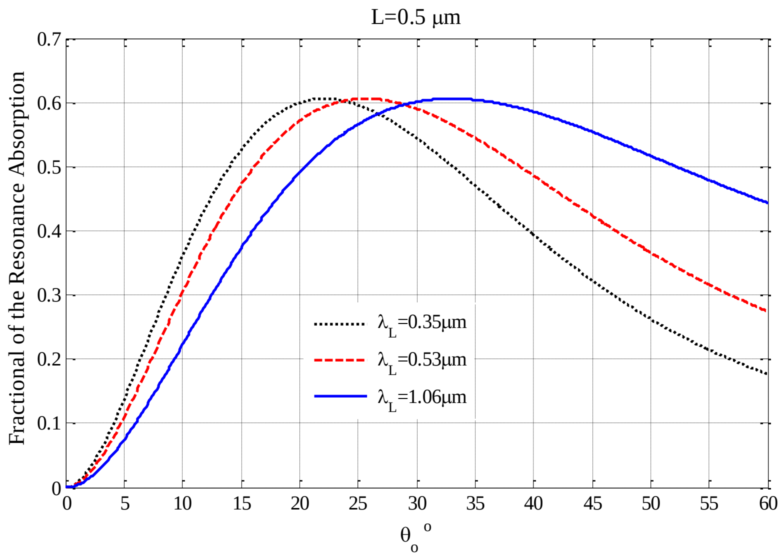

Fig. 6. The fraction of absorbed laser energy versus the incident angles for $L = 0.5\mu m$

To investigate role of the scale length of the plasma density on the resonance absorption of the laser energy, we reduced the scale length and for the three different wavelengths of the neodymium-glass laser, show the variations of the fractional absorption in Fig. 6. In this figure, for the wavelength $\lambda_L = 1.06\mu m$, the scale length of the density change is approximately half of the wavelength, and consequently the angular of the absorption peak is about 35 degrees and is about 15 degrees higher than that of Fig. 5. For $\lambda_L = 0.53\mu m$, the scale length of the plasma density is approximately equal to the laser wavelength and the maximum incident angle is about 25 degree as expected. By comparing the results of Figs. (5) and (6), it is easy to deduce that, for higher values of the scale length of the plasma density, the resonance absorption reaches the maximum value in the smaller incident angles.

4. CONCLUDING REMARKS

For various parameters, variations of the absorption coefficient are studied. The impact of temperature on the inverse braking radiation absorption is investigated numerically. Also, role of the penetration depth of laser into the corona plasma on the absorption coefficient is illustrated. Furthermore, the effect of laser wavelength on the resonance absorption is studied. Finally, for different values of incident angle, the fraction of resonance absorption is illustrated.

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REFERENCES

[1] M. Mansuri, A. Mir, A. F. orcid, *Numerical Modeling of a Nanostructure Gas Sensor Based on Plasmonic Effect,* JOPN, 4, (2019) 29.

[2] S. Pfalzner, *An introduction to inertial confinement fusion,* CRC Press (2006).

[3] J. D. Lindl R. L. McCrory, E. M. Campbell, *Progress toward ignition and burn propagation in inertial confinement fusion,* Phys. Today, 45, (1992) 32.

[4] E. Heidari, *Ultra- Relativistic Solitons with Opposing Behaviors in Photon Gas Plasma,* JOPN, 4, (2019) 27.

[5] R. Craxton et al., *Direct-drive inertial confinement fusion: A review,* Phys. Plasmas, 22, (2015) 110501.

[6] O. Hurricane et al., *Fuel gain exceeding unity in an inertially confined fusion implosion,* Nature, 506, (2014) 343.

[7] V. Gopalaswamy et al., *Tripled yield in direct-drive laser fusion through statistical modelling,* Nature, 565, (2019) 581.

[8] M. Olyaee, M. B. Tavakoli, A. Mokhtari, *Propose, Analysis and Simulation of an All Optical Full Adder Based on Plasmonic Waves using Metal-Insulator-Metal Waveguide Structure*, JOPN, 4, (2019) 95.

[9] L. M. Waganer, *Innovation leads the way to attractive inertial fusion energy reactors–Prometheus-L and Prometheus-H,* Fusion engineering and design, 25, (1994) 125.

[10] D. Eimerl et al., *Configuring NIF for direct-drive experiments. in Solid State Lasers for Application to Inertial Confinement Fusion (ICF),* International Society for Optics and Photonics. (1995).

[11] *L. Safaei, M. Hatami, M. B. Zarandi, Numerical Analysis of Stability for Temporal Bright Solitons in a PT-Symmetric NLDC.* JOPN, 2, (2017) 69.

[12] L. Safaei, M. Hatami, M. B. Zarandi. *Effect of Relative Phase on the Stability of Temporal Bright Solitons in a PT- Symmetric NLDC*, JOPN, 3, (2018) 37.

[13] R. Sato et al., *Non-uniformity smoothing of direct-driven fuel target implosion by phase control in heavy ion inertial fusion,* Scientific reports, 9, (2019) 6659.

[14] G. Pert, *The analytic theory of linear resonant absorption,* Plasma Physics, 20, (1978) 175.

[15] J. Freidberg R. Mitchell R. L. Morse, L. Rudsinski, *Resonant absorption of laser light by plasma targets,* Physical Rev. Lett., 28, (1972) 795.

[16] V. Tikhonchuk et al., *Studies of laser-plasma interaction physics with low-density targets for direct-drive inertial confinement schemes,* Matter and Radiation at Extremes, 4, (2019) 045402.

[17] W. Kruer, *The physics of laser plasma interactions,* CRC Press , (2018).

[18] S. Eliezer, *The interaction of high-power lasers with plasmas,* CRC press. (2002).

[19] O. Embréus A. Stahl, T. Fülöp, *Effect of bremsstrahlung radiation emission on fast electrons in plasmas,* New J. Phy., 18, (2016) 093023.

[20] E. I. Moses, C. R. Wuest, *The National Ignition Facility: status and plans for laser fusion and high-energy-density experimental studies,* Fusion Science and Technology, 43, (2003) 420.

[21] L. Schlessinger, J. Wright, *Inverse-bremsstrahlung absorption rate in an intense laser field,* Phys. Rev. A 20 (1979) 1934.

[22] B. Langdon, Nonlinear Inverse Bremsstrahlung and Heated-Electron Distributions, Phys. Rev. Lett. 44 (1980) 575.