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RESEARCH

Inverse bremsstrahlung absorption in laser-fusion plasma

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Abstract
Inverse bremsstrahlung absorption (IBA) is the most efficient absorption mechanism in laser-fusion plasma. IBA is the process in which an electron absorbs a photon while colliding with an ion or with another electron. IBA of laser energy in homogeneous and unmagnetized plasma has been studied using the Fokker–Planck equation. The isotropic function is considered as a q-nonextensive electrons distribution function. By considering a circular-polarized laser, kinetic theory and spherical coordinates, the first anisotropic function is calculated. A pulsed laser is considered, and the effect of the physical parameters such as temperature and q (q is a parameter quantifying the degree of nonextensivity) has been studied on the absorption value. Later, the results of continuous laser and pulsed laser have been compared. The calculations of IBA performed for a variety of q. According to our calculations, the IBA value in neighboring of the critical density layer for continuous laser is higher than pulsed laser. The final results show the IBA value increases with increase in q parameter and oppositely it decreases with temperature increasing.

Keywords Fusion · Absorption · Invers bremsstrahlung · q-nonextensive · Inertial Confinement

Introduction

Inertial confinement fusion and magnetic confinement fusion are two approaches of controlled fusion, and the IBA is an essential mechanism for coupling laser energy to the plasma in fusion [1]. After the hitting of laser light to the target, plasma layer will create immediately. In the corona of created plasma, the laser-plasma interaction is the dominant interaction. As the interaction of the laser with the target continues, distinct regions develop an absorption domain, a transport domain and a compression domain. These domains differ significantly in temperature and density [2]. Near of critical layer, the laser light is absorbed using IBA mechanism. The laser electric field causes the electron oscillation in plasma. So the energy of this oscillation via electron–ion collisions converts to the thermal energy that is called IBA. The other ways for the laser absorption into plasma are resonance absorption and parametric instabilities. Absorption using kinetic theory, in many reports, is taken into account [3–6]. IBA is calculated by Fokker–Planck simulations, too [7]. In few papers, the IBA is investigated in the hot, weakly coupled and overdense plasma [8, 9]. Here, one can use the Fokker–Planck equation which is a part of kinetic theory equations to calculate the IBA value. Fokker–Planck equation will be simplified by ignoring the electron–electron collisions $C_{\mathrm{ee}} \ll C_{\mathrm{ei}}$ and considering of the Laurentz approximation $\left(\nu_{\mathrm{ei}} \ll \omega_{\mathrm{L}}\right)$. Also, in this work we used the homogeneous and unmagnetized plasma. For the electrons, the isotropic distribution function is supposed as a q-nonextensive function. According to this electron distribution function, the anisotropic function is calculated and by obtaining of electric current density, the absorption coefficient is achieved.

The results show that in near of critical density layer, the IBA value for continuous lasers is higher than the IBA value for pulsed lasers. Also in neighboring of critical density layer, increase in q parameter leads to increase in the IBA value, and increase in electron temperature leads to decrease in the IBA value.

IBA calculations

To calculate the IBA value, electron Fokker–Planck equation for homogeneous and unmagnetized plasma is defined as [10]:

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$$\frac{\partial f}{\partial t}-\frac{e\vec{E}}{m_{\mathrm{e}}}\cdot\frac{\partial f}{\partial\vec{v}}=A\frac{\partial}{\partial\vec{v}}\cdot\left(\frac{v^2\tilde{I}-\vec{v}\vec{v}}{v^3}\cdot\frac{\partial f}{\partial\vec{v}}\right)+C_{\mathrm{ee}}(f). \tag{1}$$

where $C_{\mathrm{ei}}(f)\equiv A\frac{\partial}{\partial\vec{v}}\cdot\left(\frac{v^2\tilde{I}-\vec{v}\vec{v}}{v^3}-\frac{\partial f}{\partial\vec{v}}\right)$ and $C_{\mathrm{ee}}(f)$ are electron–ion and electron–electron collisional operators. It is good to mention that $A=\left(2\pi n_{\mathrm{e}}Ze^4/m_{\mathrm{e}}^2\right)\ln\Lambda$ wheren_{e}, m_{e} and e are the density, mass and charge of electron, respectively. $\ln\Lambda$ is the Coulomb logarithm, and Z is the ion charge number [1]. f, $\vec{v}$ and $\vec{E}$ are the electron distribution function, particle velocity and laser electric field, respectively.

We defined f as a high-frequency, f^{h}, and slow-frequency, f^{s}, parts that it oscillates at the laser frequency, ω_{L}, as [6]:

$$f(\vec{r},\vec{v},t)=f^{(\mathrm{h})}(\vec{v})e^{i\omega_{\mathrm{L}}t}+f^{(\mathrm{s})}(\vec{r},\vec{v},t). \tag{2}$$

If we expand f^{s} and f^{h}, on the Legendre polynomials, and using of f at the first order, we will have:

$$f(v,\mu,\varphi,t)=f_0(v)+\mu f_1(v,\varphi,t), \tag{3}$$

where f_0 is q-nonextensive distribution function which is defined as an isotropic function like [11, 12]:

$$f_0(v)=A_q\left[1-(q-1)\frac{m_{\mathrm{e}}v^2}{2k_{\mathrm{B}}T_{\mathrm{e}}}\right]^{\frac{1}{q-1}}, \tag{4}$$

$$A_q=\begin{cases} n_e\left(\frac{1+q}{2}\right)\frac{\Gamma\left(\frac{1}{2}+\frac{1}{q-1}\right)}{\Gamma\left(\frac{1}{q-1}\right)}\sqrt{\frac{m_e(q-1)}{2\pi k_{\mathrm{B}}T_e}} & q\geq 1\\ n_e\frac{\Gamma\left(\frac{1}{1-q}\right)}{\Gamma\left(\frac{1}{1-q}-\frac{1}{2}\right)}\sqrt{\frac{m_e(1-q)}{2\pi k_{\mathrm{B}}T_e}} & -1<q\leq 1\end{cases}. \tag{5}$$

T_{e}, k_{B} and Γ denote the electron temperature, the Boltzmann constant and the Gamma function, respectively. When $q\to 1$, $v_{\max}=\sqrt{2k_{\mathrm{B}}T_{\mathrm{e}}/m(q-1)}$ goes to infinity and Eq. (4) reduces to the standard one-dimensional Maxwell–Boltzmann distribution function. Also, f_1 is anisotropic function that can be obtained by Eqs. 1, 3 and 4 using the spherical coordinates (v, $\mu=\frac{v_x}{v}$, $\varphi=\arctan v_z/v_y$). Using of laser circular-polarized electric field as:

$$\vec{E}(x,t)=E_0(x)\exp\left(i\omega_{\mathrm{L}}t\right)(\hat{y}+i\hat{z}), \tag{6}$$

and $\vec{J}(x,t)=-en_{\mathrm{e}}\vec{v}(x,t)$, the electric current in the plasma, and $n_{\mathrm{e}}=\int fd^3\vec{v}$, we can calculate the IBA value. In a hot plasma when $\hbar\omega_{\mathrm{L}}\ll T_{\mathrm{e}}$, the classical and quantum descriptions of laser-plasma interaction agree to each other, and then, absorption, $Ab=\vec{E}\cdot\vec{J}$ is expressed as:

$$\mathrm{Ab}=\mathrm{Re}\left(\frac{\vec{E}^*(x,t)\cdot\vec{E}(x,t)}{k_{\mathrm{B}}T_{\mathrm{e}}}\int_0^\infty\frac{4\pi A_qe^2v^4}{3\left(i\omega_{\mathrm{L}}+\frac{2A}{v^3}\right)}\left[1-(q-1)\frac{m_{\mathrm{e}}v^2}{2k_{\mathrm{B}}T_{\mathrm{e}}}\right]^{\frac{2-q}{q-1}}\mathrm{d}v\right), \tag{7}$$

where $\vec{E}^*(x,t)$ shows the complex conjugate of $\vec{E}(x,t)$. So we get:

$$\mathrm{Ab}=\left(\frac{32\pi^2n_{\mathrm{e}}^2Ze^6}{3\omega_{\mathrm{L}}^2}\right)\ln\Lambda E_0^2\left(\frac{1+q}{2}\right)\frac{\Gamma\left(\frac{1}{2}+\frac{1}{q-1}\right)}{\Gamma\left(\frac{1}{q-1}\right)}\sqrt{\frac{(q-1)}{2\pi k_{\mathrm{B}}T_{\mathrm{e}}m_{\mathrm{e}}^5}}. \tag{8}$$

According to the Airy–Hora's function [13, 14], we will have:

$$\vec{E}_0(x)=2\pi^{\frac{1}{2}}\rho^{\frac{1}{6}}E_\nu\exp(-s)\mathrm{Airy}(-\xi), \tag{9}$$

where

$$s=\left(\frac{-\nu_{\mathrm{ei}}}{\omega_{\mathrm{L}}}\right),\quad \rho=\left(\frac{L_n\omega_{\mathrm{L}}}{c}\right), \tag{10}$$

$$\xi=\rho^{2/3}\left(-x/L_n+is\right), \tag{11}$$

E_ν is the laser electric field magnitude in vacuum and c stands for the light speed. $L_n\approx C_{\mathrm{s}}\tau_{\mathrm{L}}$ shows the electron density gradient, whereas τ_{L} and C_{s} are the laser pulse length and the ion acoustic speed, respectively.

Finally, we obtained:

$$\mathrm{Ab}=\left(\frac{32\pi^2Zn_{\mathrm{e}}^2e^6}{3\omega_{\mathrm{L}}^2}\right)\left(2\pi^{\frac{1}{2}}\left(\frac{L_n\omega_{\mathrm{L}}}{c}\right)^{\frac{1}{6}}E_\nu\exp(-s)\mathrm{Airy}(-\xi)\right)^2 \left(\frac{1+q}{2}\right)\frac{\Gamma\left(\frac{1}{2}+\frac{1}{q-1}\right)}{\Gamma\left(\frac{1}{q-1}\right)}\sqrt{\frac{(q-1)}{2\pi k_{\mathrm{B}}T_{\mathrm{e}}m_{\mathrm{e}}^5}}\ln\Lambda. \tag{12}$$

This equation expresses the absorption value for continues lasers.

The absorption value for pulsed laser using $\vec{E}(x,t)=E_0(x)\exp\left(i\omega_{\mathrm{L}}t\right)\sin^2\left(\pi\frac{t}{\tau_{\mathrm{L}}}\right)(\hat{y}+i\hat{z})$ with the same calculations is obtained [15].

Results and discussion

A continuous laser is considered, and the effect of physical parameters such as temperature and the strength of nonextensivity, q, has been studied on the inverse bremsstrahlung absorption value. The IBA value for $q=2$ determined for the both of continuous and pulsed lasers that one can see in Figs. 1 and 2.

Figure 1 shows the absorption (IBA) as a function of x/L_n for a continuous laser that its value in near of the critical density layer is about 1.6×10^{14} W/m^3, whereas Fig. 2 depicts the IBA value for the pulsed laser that IBA value is about 5.6×10^{13} W/m^3 close to the critical density layer.

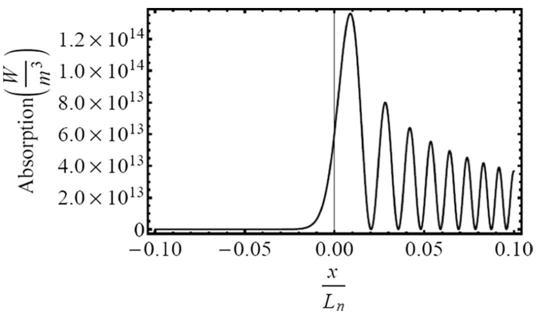


Fig. 1 Absorption as a function of x/L_n for continues laser. In near of the critical density layer ($x = 0$), absorption is maximum. The laser and plasma parameters are as follows: $Z = 4$,$q = 2$, $T_e = 10$ keV, $L_n \cong 0.0028$ m, $\lambda_L = 10.6$ µm

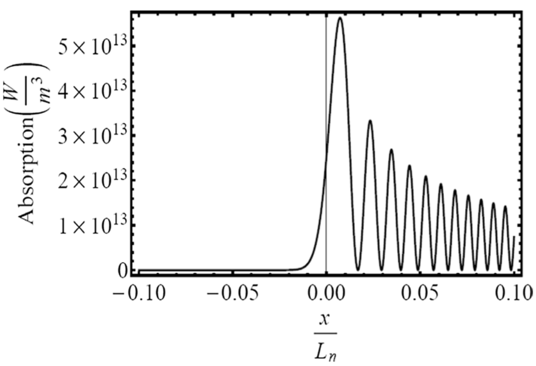


Fig. 2 Absorption as a function of x/L_n for pulsed lasers. In near of the critical density layer ($x = 0$), absorption is maximum. The laser and plasma parameters are:$Z = 4$,$q = 2$, $T_e = 10$ keV, $L_n \cong 0.0028$ m, $\tau_L = 4$ ns, $\lambda_L = 10.6$ µm

The regions of $x/L_n < 0$ and $x/L_n > 0$ denote the regions of overdense plasma and underdense plasma, respectively. To achieve high-temperature and high-density plasmas for driving the fusion reaction, we need initially high energy and preserve the confinement conditions. The pulsed lasers with short pulse length cannot provide confinement conditions as well as continuous lasers. Thus, if we use a 4 ns pulse length laser (Q-switched Nd:YAG [16]), the IBA value will be lower than its value in comparison with continuous laser. Our previous results showed that increase in pulse length leads to increase in IBA value [14].

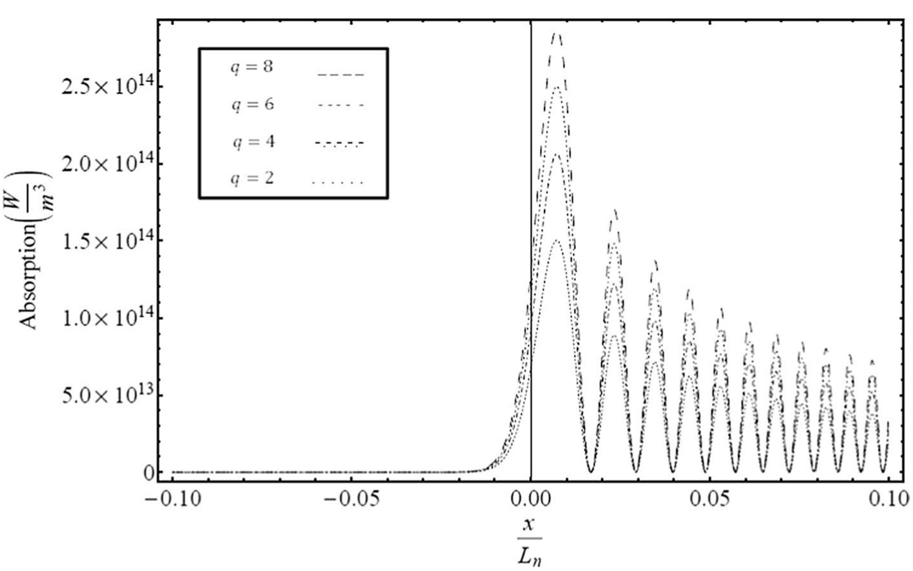
Figure 3 shows the effect of q-parameter on the absorption (IBA). This figure depicts that the increase in the absorption is due to the increase in q. As we can see, for the constant electron density gradient ($L_n \cong 0.0028$ m) and using Eq. 12, the absorption value in near of the critical density layer for $q = 2$ is about 1.4×10^{14} W/m^3, whereas it is around 2.9×10^{14} W/m^3 for $q = 8$.

Figure 4 shows absorption as a function of electron temperature. As one can see, in this figure increase in temperature causes the decrease in absorption.

Conclusion

We used the Fokker–Planck equation and kinetic theory in laser fusion plasma; then, the anisotropic distribution function, electrical current density and the absorption are calculated. As shown in Figs. 1 and 2, the absorption value for continuous laser is larger than it in pulsed laser neighboring of critical density layer. Figures 3 and 4 denote the effect of q-parameter and electron temperature on the inverse bremsstrahlung absorption value. For higher degree of nonextensivity (q-parameter), the IBA increases,

Fig. 3 Absorption versus function of x/L_n. The laser and plasma parameters are:$Z = 4$,$L_n \cong 0.0028$ m, $T_e = 10$ keV, $q = 2$ to $q = 8$, $\lambda_L = 10.6$ µm



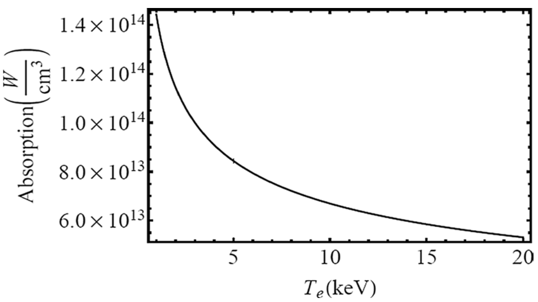


Fig. 4 Absorption as function of electron temperature using continues lasers for $q = 2$

whereas increase in electron temperature leads to decrease in absorption.

References

1. Eliezer, S.: The Interaction of High-Power Lasers with Plasmas. IOP Publishing Ltd, Bristol (2003)
2. Pfalzner, S.: An Introduction to Inertial Confinement Fusion. Taylor & Francis/CRC Press, Boca Raton (2006)
3. Porshnev, P., et al.: Nonlinear inverse bremsstrahlung and highly anisotropic electron distributions. Phys. Rev. E **53**(1), 1100 (1996)
4. Bendib, A., Luciani, J.: Collisional effects and dispersion relation of magnetic field structures. Phys. Fluids (1958–1988) **30**(5), 1353–1361 (1987)
5. Bendib, A., Bendib, K., Sid, A.: Weibel instability due to inverse bremsstrahlung absorption. Phys. Rev. E **55**(6), 7522 (1997)
6. Sid, A.: Nonlinear inverse bremsstrahlung absorption in laser-fusion plasma corona. Phys. Plasmas **10**, 214 (2003)
7. Weng, S.-M., et al.: Inverse bremsstrahlung absorption and the evolution of electron distributions accounting for electron-electron collisions. Phys. Plasmas (1994–Present) **13**(11), 113302 (2006)
8. Wierling, A., et al.: Inverse bremsstrahlung of hot, weakly coupled plasmas. Phys. Plasmas **8**, 3810 (2001)
9. Yang, T.Y.B., et al.: Absorption of laser light in overdense plasmas by sheath inverse bremsstrahlung. Phys. Plasmas **2**, 3146 (1995)
10. Kruer, W.L.: The Physics of Laser Plasma Interactions, vol. 70. Addison-Wesley, New York (1988)
11. Lima, J., Silva Jr., R., Santos, J.: Plasma oscillations and nonextensive statistics. Phys. Rev. E **61**(3), 3260 (2000)
12. Sharifian, M., et al.: Effect of q-non-extensive distribution of electrons on the plasma sheath floating potential. J. Plasma Phys. **80**, 607–618 (2014)
13. Hora, H.: Laser Plasmas and Nuclear Energy, vol. 1. Plenum Press, New York (1975)
14. Abramowitz, M., Stegun, I.A.: Handbook of Mathematical Functions: With Formulas, Graphs, and Mathematical Tables. Courier Dover Publications, Mineola (1972)
15. Farrashbandi, N.F., et al.: Investigation of the effect of laser pulse length on the inverse bremsstrahlung absorption in laser-fusion plasma. High Energy Density Phys. **16**, 32–35 (2015)
16. Dallas, J., Afzal, R., Stephen, M.: Demonstration and characterization of a multibillion-shot, 2.5-mJ, 4-ns, Q-switched Nd: YAG laser. Appl. Opt. **35**(9), 1427–1429 (1996)