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Enhancement of Electron Temperature under Dense Homogenous Plasma by Pulsed Laser Beam

Khalid A. Yahya

Department of Physics, College of Science, Al-Nahrain University, Baghdad, Iraq.
E-mail: drkayahya2005@yahoo.com
ORCID ID: https://orcid.org/0000-0001-8760-0962

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Abstract:

The applications of hot plasma are many and numerous applications require high values of the temperature of the electrons within the plasma region. Improving electron temperature values is one of the important processes for using this specification in plasma for being adopted in several modern applications such as nuclear fusion, plating operations and in industrial applications**.** In this work, theoretical computations were performed to enhance electron temperature under dense homogeneous plasma. The effect of power and duration time of pulsed Nd:YAG laser was studied on the heating of plasmas by inverse bremsstrahlung for several values for the electron density ratio. There results for these calculations showed that the effect of increasing the values of the laser pulse power (25-250kW) led to decrease the absorption coefficient values by 58.3% and increase the electron temperature by 50.0% at duration pulse time 0.5ns and electron density ratio 0.1. Furthermore, the ratio of electron density increasing and pulse duration time led to increase the higher values of the electron temperature**.** The results of the calculations showed the effect of the laser power, the percentage of electron density, and the pulse duration for improving the electron temperature. It is possible to control the temperature of the electrons with one of the plasma parameters or the laser beam used, and that it gives a clear indication of researchers in this field to choose the optimal wavelength of the laser beam and electron density ratios for the plasma.

Keywords: Absorption coefficient, Gaunt factor, Heating plasma, Inverse bremsstrahlung, Under dense plasma

Introduction:

Electron temperature is the primary measurement of the kinetic energy of electrons inside plasma. The electron temperature is an important parameter in determining the classification of the plasma (thermal and non thermal) by comparing its values with the temperature of the ions inside the plasma. Therefore, the researchers focused on this parameter in order to change the values of electron temperature according to the requirements of practical applications such as including nuclear fusion, plating operations and in industrial applications(1,2,3).There are several methods for heating plasma and varying the electron temperature values such as, applying a magnetic field or interacting by a laser beam with plasma (4,5,6,7).The process of energy absorbing of the laser beam occurs by inverse bremsstrahlung (IB). The (IB) process refers to absorb the energy of the photons by plasma electrons and gaining energy leads to heating the plasma and raising the temperature of the electrons. These are carried out with two techniques collisionless and collisional process.

In collisionless technology, the free electrons are absorbed of the photon's energy directly while in collisional technology, the energy of the electrons will be transferred to the neutral ions and atoms by colliding (8, 9).

In this work, theoretical computations were done by solving equations for the interaction of the laser beam pulse with the plasma region to study the parameters affecting for the absorption coefficient of the laser beam energy and plasma heating in (IB) method.

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Theory:

In this propose model, the homogenous plasma heating phenomenon using inverse bremsstrahlung absorption was studied by using pulsed neodymium laser beam with Gaussian distribution shape .

The type of the interaction(under dense or over dense plasma) can be determined according to the values of critical density of plasma (n_c) and unitless laser amplitude(a_o) as the following(10,11) :

$$n_c(cm^{-3}) = \frac{1.1x10^{21}}{\lambda^2(\mu m)} \quad 1$$

$$a_o = 8.65x10^{-10}\ \lambda(\mu m)\ I^{1/2}(W/cm^2) \quad 2$$

Where λ and I are the wavelength and intensity of laser pulse respectively. So, the case of under dense plasma type is achieved when $n_c > n_e$ or $\omega_L > \omega_p$ where n_e is the plasma electron density, ω_L is the angular frequency of laser beam and ω_p is the plasma frequency. Also, the over dense plasma type is achieved at the reverse of these conditions. On the other hand, the value of a_o is used for distinguishing the type of interaction region (non-relativistic at a_o<1 and relativistic at a_o>1).

The research includes the study of the parameters affecting the heated homogenous plasma using inverse bremsstrahlung absorption (IB) interaction pulsed laser beam with plasma. Furthermore, the Gaussian shape is assumed for pulses temporal laser beam tacks a form (12)

$$P(t) = P_{max}\ \exp\left[(-4\ln 2)\left(\frac{t}{\tau_p}\right)^2\right] \quad 3$$

Where P_{max} is a peak power of laser pulse, t is time step and τ_p is full width at half for laser pulse duration. In the case of liner (IB), the absorption coefficient $\alpha(T_e)$ in m^{-1} is given by (13)

$$\alpha(T_e) = Z\, n_o^2\, (1-n_o)^{-0.5}\, (k_B\, T_e)^{-1.5}\ \bar{g}(T_e)\ 10^5 \quad 4$$

Where the ratio electron density $n_o = n_e/n_c$, T_e is temperature of electron in (eV) , k_B is Boltazmaan constant, Z is ion charge and $\bar{g}(T_e)$ is the average gaunt factor in hydrodynamic approach (the quantum effect is ignored) given by(14)

$$\bar{g}(T_e) = \frac{\sqrt{3}}{\pi}\ln\left(\frac{(2\,k_B\,T_e)^{3/2}}{\pi\,\varepsilon_o^2\, m_e^{1/2}\, e\,\gamma_g\,\nu}\right) \quad 5$$

Where m_e is electron mass, ν is laser beam frequency and γ_g is a constant called Euler-Mascheroni = 1.781 (14).

The energy absorbed by the electrons in plasma from the laser beam per unit length $Q_A(t)$ is given by eq.(6)

$$Q_A(t) = P(t)\ t\ \alpha(T_e) \quad 6$$

The amount of increases in the electron temperature $Te_{(add)}(t)$ is calculated from the equation

$$T_{e(add)}(t) = \frac{Q_A(t)}{n_o\ A} \quad 7$$

where A= π r^2 is the area of laser beam with a radius r.

So ,it can be calculated the new values of electron temperature $T_{e\ (new)}(t)$

$$T_{e(new)}(t) = T_{e(old)}(t) + T_{e(add)}(t) \quad 8$$

Results and Discussion:

The proposed model included a pulsed Nd:YAG laser at wavelength λ =1.06 µm and radius beam 100 µm interacting with homogenous plasma at initial electron temperature T_e = 3 eV and Z=1. According to eq.1, the critical density n_c = 9.7899x10^{20} cm^{-3}, and using the range of the electron density ratio n_o (0.1- 0.7), so $n_c > n_e$ and the case was under dense as mentioned. The computations were done with the aid of equations 1 to 8 to study the effective parameters for heating a plasma region by a pulsed laser beam as the following:

Laser pulse profiles

The research adopted the Gaussian profile of the Nd:YAG laser pulse with a wavelength 1.06 µm ,which interacted with the plasma region. It takes the form in eq.3, and for five values of peak power laser beam (25, 75,125,175and250kW) as shown in Fig.1.

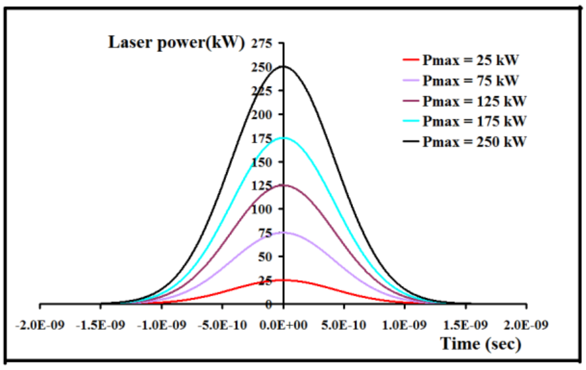

Figure1. Profiles of Nd:YAG pulsed laser beam for different values of peak power at duration time τ_p= 5x10^{-5} sec.

Absorption of pulsed laser

The effect of changing the maximum power of the pulsed Nd:YAG laser with the plasma on the inverse bremsstrahlung absorption coefficient was studied as in Fig.2. The absorption coefficient values decreased with increasing laser beam power. The reason for this behavior is that in collisional absorption method, as increasing the beam power the laser beam will spread and propagated through the plasma without transferring its energy to the electrons, thus the absorption coefficient will decrease(6).

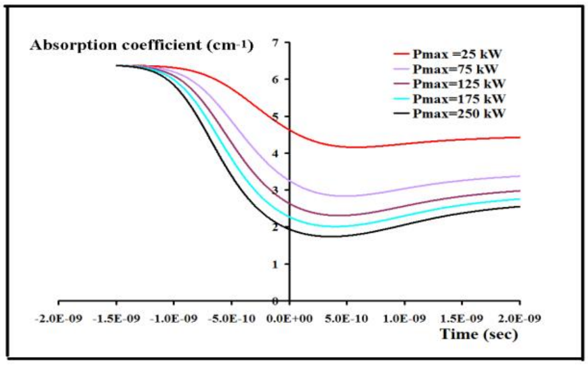

Figure 2. Absorption coefficient verse duration time pulsed Nd:YAG laser beam for different values of peak power at n_o=0.1 and τ_p=5x10^{-10} sec.

Figure3 shows the relationship of the minimum value of the absorption coefficient as a function of electron density ratio n_o for several values of the higher value of peak power and duration time of laser pulse.

It is observed that with increasing density values, the minimum absorption coefficient values increase. Also, when the peak of the laser power pulse increases, it leads to a decrease in the minimum values of the absorption coefficients. On the other hand, the increase in the pulse duration time leads to a decrease in the minimum absorption coefficient values. The results obtained from Figs2 and3 are similar to those obtained by Abolfazl et al (6) in terms of behavior.

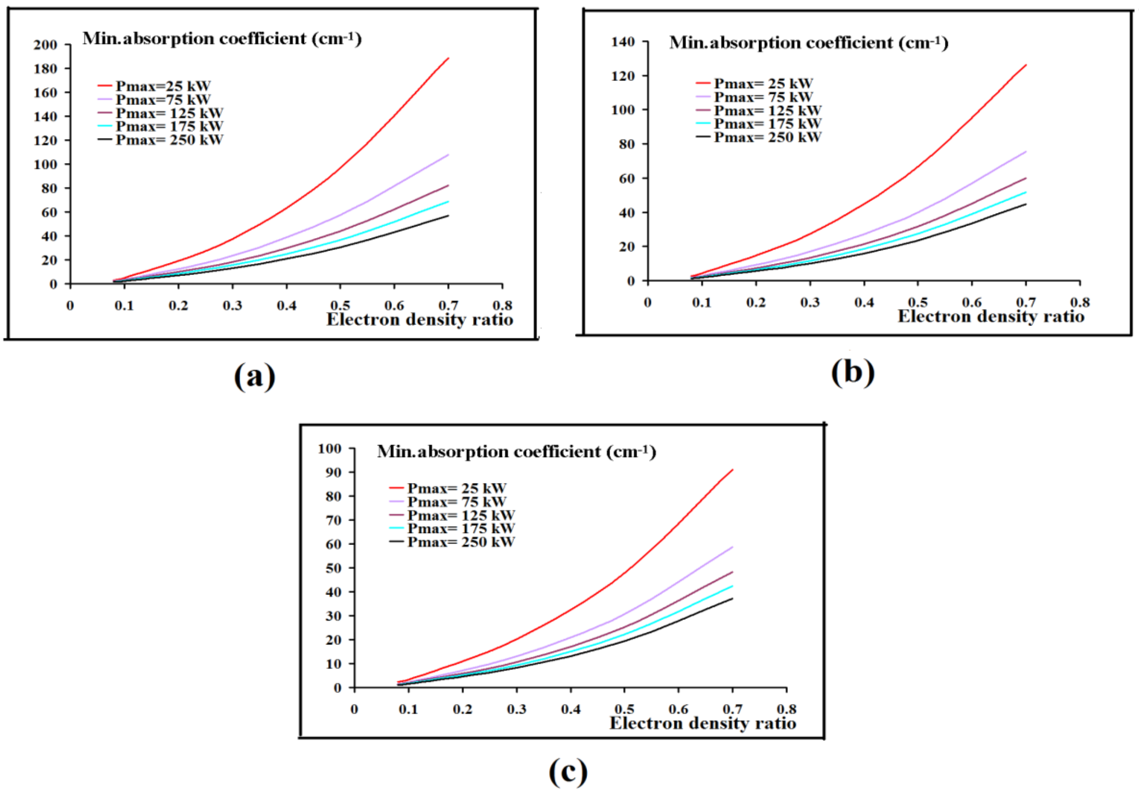

Figure 3. Minimum absorption coefficient as a function of electron density ratio for different peak power laser pulsed values at (a) τ_p = 2x10^{-10} sec, (b) τ_p = 5x10^{-10} sec and (c) τ_p= 12x10^{-10} sec.

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Heating under dense plasma by laser pulse

The inverse bremsstrahlung absorption of the laser beam in under dense plasma region and the effective parameters on the values of plasma electron temperature at initial value 3eV were studied as the following:

Peak power of the laser beam

The effect of the peak values power of the pulsed Nd:YAG laser on the electron temperature in the plasma with n_o= 0.1 and the time for duration pulse $5x10^{-10}$ sec were calculated as shown in Fig. 4

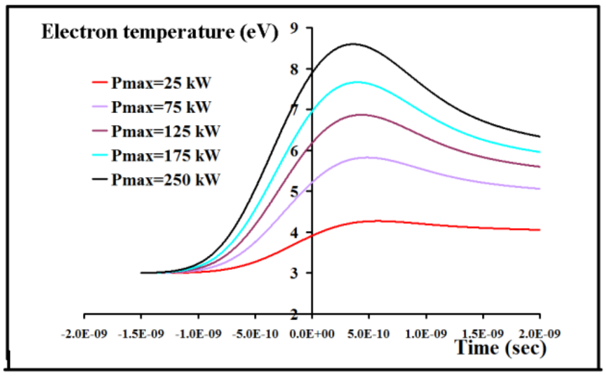
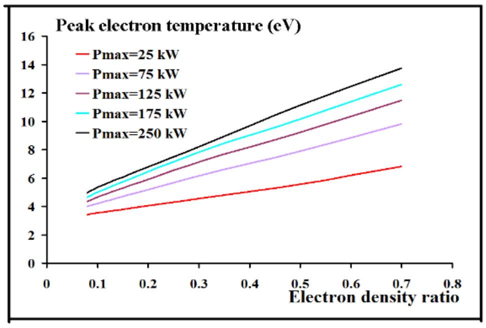


Figure 4. Plasma temperature electron as a function of time at τ_P= $5x10^{-10}$ sec, n_o=0.1 and Te=3 eV for different peak power of Nd:YAG pulsed laser.

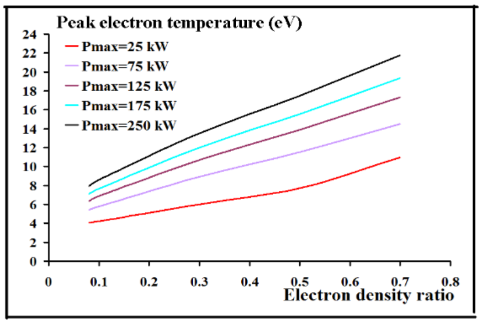
It is clear from the figure that the enhancement of electron temperature values was achieved with increasing the peak power of the pulsed laser beam. The decrease in the absorption coefficient values as in Fig 2 led to an increase in the electron temperature values, which was the same behavior that Rozmus and Tikhonchuk and Ettehadi-Abariet al (15,16).

Electron density ratio and pulsed duration time

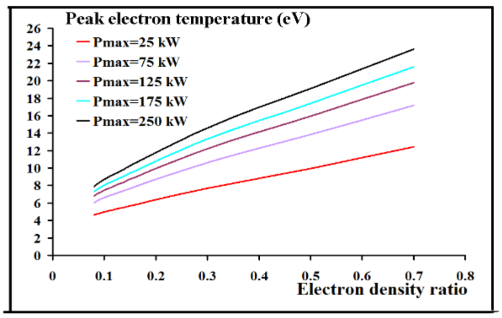
Figure 5 shows the effects of changing the ratio values of electron density from (0.1- 0.7) on the peak temperature electron values inside the plasma after its interaction with the laser pulse with different values of peak power and duration times. It has been observed that with an increase in the density ratio and laser power, the peak values of the temperature electron increase. Also, it was evident that increasing of peak electron temperature increased the duration of pulsed time. The same behavior was obtained for the results of Unnikrishnan et al (17).



(a)



(b)



(c)

Figure 5. Peak electron temperature verse the ratio of electron density with initial T_e =3 eV for different peak power laser pulsed at (a) τ_P = $2x10^{-10}$ sec, (b) τ_P = $5x10^{-10}$ sec and (c) τ_P= $12x10^{-10}$ sec.

Conclusions:

By inverse bremsstrahlung absorption of Nd:YAG laser pulses, the heated homogeneous plasma is studied with different values of plasma densities ratio and peak power and duration time of a pulsed laser beam. The increase in the power values of the laser pulses leads to decrease in the absorption coefficient values by a ratio of 58.3% at changing the power values from 25 to250 kW.

The electron density ratio values play an important role in the interaction between the laser pulse and the plasma. So, the increases in their ratios lead to an increase in the minimum values of the absorption coefficient by 64.6% at duration pulse time 0.5 ns density ratio o.1. Also, the increase in duration time causes for a decrease in the minimum values for the absorption coefficient. On the other hand, the power values of laser pulse has a significant impact on increasing the electron temperature values by 50.0% when increasing their values from 25 to 250 kW at duration pulsed time 0.5 ns and density ratio 0.1. It is also noted that the increasing of the ratio of electron density and pulse duration time leads to increasing the peak values of the electron temperature.

Author's declaration:

- Conflicts of Interest: None.
- I hereby confirm that all the Figures and Tables in the manuscript are mine. Besides, the Figures and images, which are not mine, have been given the permission for re-publication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in Al-Nahrain University.

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تحسين درجة حرارة الإلكترون في بلازما متجانسة تحت الكثيفة با ستخدام شعاع ليزر نبضي

خالد عباس يحيى

قسم الفيزياء، كلية العلوم ، جامعه النهرين، بغداد، العراق.

الخلاصة:

ان تطبيقات البلازما الساخنة كثيرة ومتعددة ويتطلب في الكثير من التطبيقات الحصول على قيم عالية لدرجة حرارة الالكترونات داخل منطقة البلازما. تعتبر عمليات تحسين قيم درجات حرارة الالكترونات من العمليات المهمة لغرض استخدام هذا المواصفات في البلازما لغرض اعتمادها في عدة تطبيقات حديثة ومجالات واسعة منها عمليات الاندماج النووي وعمليات الطلاء وفي التطبيقات الصناعية كقطع المعادن والطلاء. من التقنيات المستخدمة في تسخين البلازما استخدام تقنية تسليط المجال المغناطيسي على البلازما باستخدام مغانط ذات فيض مغناطيسي عالي و استخدام تقنية حزمة الالكترونات في التسخين وكذلك استخدام شعاع الليزر والذي تم اعتماد هذه الطريقة في هذا البحث .في هذا العمل أجريت حسابات نظرية لتحسين درجة حرارة الإلكترون في البلازما المتجانسة تحت الكثيفة باستخدام تقنية الليزر حيث تمت دراسة تأثير قدرة ومدة زمن النبضة لشعاع ليزر Nd:YAG ذو الطول الموجي = 1.06 μm على تسخين البلازما بواسطة inverse bremsstrahlung لعدة قيم لنسبة كثافة الإلكترون. أوضحت نتائج هذه الحسابات أن تأثير زيادة قيم طاقة نبضة الليزر (25-250 كيلووات) أدى إلى انخفاض قيم معامل الامتصاص بنسبة 58.3٪ وزيادة درجة حرارة الإلكترون بنسبة 50.5٪ عند زمن النبضة 0.5 نانو ثانية. ونسبة كثافة الإلكترون 0.1. علاوة على ذلك، أدت نسبة زيادة كثافة الإلكترون ومدة النبض إلى زيادة القيم الأعلى لدرجة حرارة الإلكترون.وقد بينت نتائج الحسابات تأثير العوامل قدرة الليزر ونسبة كثافة الالكترونات ومدة النبضة في التأثير المباشر على تحسين درجة حرارة الالكترون من نتائج هذه الحسابات انها اعطت نتائج تبين فيها انه من الممكن السيطرة على درجة حرارة الالكترونات باحدى عوامل البلازما او شعاع الليزر المستخدم وانها تعطي اشارة واضحة الى الباحثين بهذا المجال لاختيار الطول الموجي لشعاع الليزر الامثل وكذلك اختيار نسب الكثافة االكترونية للبلازما في البحث. لان الاساس والذي تم توضيحه هو معامل الامتصاص وقد بيينت نتائج الحسابات اهمية هذا العامل في نجاح عملية تسخين البلازما . وايضا من النتائج المستحصلة هو اهمية مواصفات قيم قدرة الليزر ومدة نبضة الشعاع المستخدم حيث بينت النتائج ان بزيادة القدرة والكثافة الالكترونية ادت الى زيادة عمليات التسخين.

الكلمات المفتاحية: معامل الامتصاص،معامل كانت، تسخين البلازما، الكبح العكسي، بلازما تحت الكثيفة.