RELATIVISTIC INTENSITY DEPENDENCE OF ABSORPTION PROCESSES IN LASER PRODUCED PLASMA

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ABSTRACT: *The problem of the interaction of an ultrastrong laser pulse within the framework of the quasifree state of an electron dressed by a strong laser field was studied recently. A simple and useful approximation is obtained for the multiphoton energy transfer processes which accompany the relativistic scattering of a charged particle and an effective collision frequency was found. Under this conditions the classical linear resonance is unable to explain the global absorption in laser – plasma experiments. In this paper, when the absorption rate is independence of the initial distribution function and depends only on the photon flux intensity, we show that the effective absorption coefficient is scale as* I^r, *where the r- parameter is in the range of* $0.5 \le r \le 0.75$. *This scale factor is compared with the recent Brunel' expression and the results obtained from experimental conditions.*

1. INTRODUCTION

The interaction of ultrahigh – power beams with plasma through the non linear inverse Bremsstralung become particulary interesting when the laser power is sufficiently intense to cause the electron oscillation (quiver) velocity to became highly relativistic. At present, the investigation of the relativistic absorption of intense electromagnetic radiation through electron – ion collision processes in a fully ionized plasma is still incomplete. The major difficulty with the existing theories at high radiation intensities is because of large numbers of photon which must be included and, in these case, the direct evaluation of the contributions from many photons to obtain the total absorption coefficient is very difficult.

Recently [1], (hereafter referred to as I), through a simple quantum mechanical approach, the inverse Bremsstrahlung problem for CO_2 laser-plasma interaction was studied by calculating the transition probability [2] per unit time and the rate at which energy is absorbed by electrons with a specified energy distribution, where we find that $\gamma_{eff} \sim I^p$, $(p \le 1/2)$. However this scale factor is usefull to model CO_2 laser-plasma experiments when the density gradient length L, does not depend on the laser intensity.

At high laser intensity when the energy of a free electron oscillating in a strong laser field, can exceed its rest energy, m_0c^2, an analysis of the processes by which photons are absorbed, by which the heating occurs and by which the energy is redistributed between electrons and ions presents still some difficulties because L = L(I). The aim of this paper is to give a simple scaling law for the absorption coefficient $\alpha(I)$, based on the theory presented in ref I, which allows to model CO_2 as well as Nd-Yag laser-plasma experiments, when $L = I^s$, being s < 1 at high laser intensities.

2. EFFECTIVE COLLISION FREQUENCY AND ABSORPTION COEFFICIENT

The typical calculating of the effective collision frequency is based on a model of the electron kinetic equation [3]. For high laser flux, specially when the electron temperature rises by several orders of magnitude over the initial value, as it was shown in ref I, the absorption rate is independent of the initial distribution function For CO_2 laser-plasma interactions, it was assumed that the incident electron beam is represented by a delta function, $\delta(v_{te}, I)$. Here, in order to include Nd-Yag-laser-target interaction, we assume that the normalization factor of $f(v)$ does not depend of I.

$$f(v) = \frac{n_e \delta\left[v - \left(v_{te}^2 + \alpha I\right)^{1/2}\right]}{4\pi\left[v_{te}^2\right]} \qquad (1)$$

where we set $v_0^2 = \alpha I$; v_{te} is the thermal electron velocity and $\alpha^{-1} = I / v_0^2$. This approximation is useful for $v_0 / v_{te} = 0.4\lambda\sqrt{I} / \sqrt{T_e} \geq 1$ and $(v_0 / c)^2 < 1$ is given in micron, I in 10^{15} W/cm^2 and T_e in KeV, [2].

The effective collision frequency is calculated as

$$\gamma_{eff} = \int v\sigma(v) f(v) d^3v \qquad (2)$$

taking $\varepsilon \to 1$ and

$|\phi(k)|^2 \to 1$ (normalized Coulomb potential), γ_{eff} was scaled as

$$\gamma_{eff} \sim \frac{8\pi e^{e\delta} n}{m^2\left(\vartheta_{te}^2 + \alpha I\right)^{1/2}} R(I) \ln\left(\frac{k_{max}}{k_{min}}\right), \qquad (3)$$

where, $\ln\left(\frac{k_{max}}{k_{min}}\right) \sim \ln\left(\frac{v_o}{\omega r_c}\right)$ for $v_o / \omega \rangle\rangle r_c$ and $Ze^{e} \rangle h\nu$, or

$$\ln\left(\frac{k_{max}}{k_{min}}\right) \sim \ln\left(\frac{m v_o^2}{\hbar\omega}\right) \text{ for } (h\omega / m)^{1/2} \langle\langle v_o$$

and $r_c = 4e^2 / m v_o^2; v_o = eE_o / m\omega$ (see Silin [5]).

From equation 3 we can obtain several asymptotic results, for the weak-field case we have

$$\gamma_{eff} \sim \frac{8\pi e^4 n}{m^2 v_{te}^3} \ln\Lambda \qquad (4)$$

Equation 4 agrees with SiLin's and Seely'expression [5, 3].

At high beam intensity, when elastic collisions are considered, R(I) = 1 so γ_{eff} is scaled as $\gamma_{eff} \sim I^{-1/2}$ which is similar to the scale founded by Nicholson [4]. However for inelastic collision, $R(I) \sim 1 + \alpha I / v_{te}^2$ and γ_{eff} becomes approximately can be compared with the early result of Silin ($\gamma_{eff} \sim I^{-3/2}$ [5]).

In the relativistic regime, (CO_2), $v_o \leq c, R(I) \sim \left[1 + (v_O / C)^2\right]^2$, so if we extend this result for $v_o \equiv \frac{eE_O}{m\omega} \rangle c$ we have (see ref. I)

$$\gamma_{eff} \sim \frac{8\pi e^{e\delta} n}{m^2\left(v_{te}^2 + \alpha I\right)^{1/2}} \ln\Lambda\left[1 + \left(\frac{v_o}{c}\right)^2\right]^{-1/2} \sim I^p \qquad (5)$$

where $1 < p < 1.25$, here we have considered that the hot electron temperature is scale as $T_{hot} \sim I^{1/2}$ [6], [7].

Equation (5). is the main result of this paper, because clearly it shows an enhanced collision frequency which is usefull to estimate the absorption coefficient.

It was early reported that the coefficient of absorption of CO_2, (Nd-Yag) laser light by spherical targets has a nonlinear dependence on the laser intensity I, for $I \geq 10^{15} W/cm^2 (I \geq 10^{16})$ [8], [9] and [10]. The observed dependence of the absorption coefficient, α, on the laser intensity was early interpreted as an enhancement of resonant absorption due to a distribution of the critical surface. However it is simple to show that the resonant absorption is unable to explain the experimental observations. The maximum energy stored in the resonant field is $W_r = (E_r^2 / 8\pi) l$, where the length l at wave breaking is approximately $l = v_r / \omega_o = (2 v_o l \omega_o)^{1/2}$ with $v_r = eE_r / m\omega_r$.if all this energy is lost, it will take a time $t_r \sim (8L / v_o \omega_o)^{1/2}$ to rebuild. Thus the highest absorption rate is $I_{abs}/I_o \sim k_o L$. When the incident irradiance, and consequently the ponderomotive force increases, increasingly steep density gradients are established to maintain the dynamic equilibrium, that is, the critical density scale length L decrease with increasing incident radiation. Experimentally, above $I = 10^{14}$, $L \sim I^{-1/2}$ [6] so for $v_o / \omega_o \geq L$ the resonant absorption mechanism is quenched. Also, a change in the scale length, L(I), will cause a change in the scaling with I of the resonant field amplitude and therefore of the hot electron temperature. Experimentally it was found that the hot electron temperature is scale as $T_{hot} \sim I^{0.5}$. Unfortunately, no calculation has been done to support these qualitative remarks. Here we propose that the observed intensity dependence of α results from the nonlinear effects in the quasi-relativistic inverse Bremsstrahlung by the preheated electrons in the corona.

With a simple calculating, we can show that the absorption coefficient α is proportional to $(\gamma_{eff} / \omega_o) k L$ [2], so from equation (5) we see that α is scale as I^r where $1/2 \leq r \leq 3/4$. The same scale factor was obtained theoretically by Brunel [6] using a classical non resonant process. However the dependence of the absorption coefficient with the laser intensity comes from a different mechanism. Experimentally [8], [9], [10]. It was reported that the laser absorption in a gold target increase with laser intensity when $I > 10^{15}$ W/cm^2, and it seems that $\gamma_{eff} \sim I^p, p \geq 0.5$ [8], [9]. This apparently agree with our estimation of plasmas at 1.0 micrometer. It seems that our result is more appropriate to model CO_2 laser-plasma experiments. Our estimates are based on qualitative arguments where the basic behavior of high energy process evolving relativistic electrons are determined by the total electron energy in the wave field. The precise nature of the plasma dynamics that leads to higher absorption is not fully understood. However from this work, one general observation is pertinent: the absorption increase as the electron becomes relativistic that is, when $T_{hot}/mc^2 \sim 1$, where m is the electron rest mass and T_{hot} is the superthermal electron temperature in the plasma. For plasma irradiated by CO_2 lasers at $I > 10^{16}$ W/cm^2 [8], [9], T_{hot} is in the range of 200 KeV. The observation also is confirmed by calculating from the plasma simulation code WAVE [11].

In summary, we have calculated a simple expression for the effective collision frequency that takes in to account the laser intensity, which is scale as $\gamma_{eff} \sim I^{1-1.25}$ and this can be considered as an enhanced Bremsstrahlung. With this γ_{eff} we are able to obtain the absorption coefficient, which is scale as $\alpha \sim I^{1/2-3/4}$.

SỰ PHỤ THUỘC CƯỜNG ĐỘ TƯƠNG ĐỐI CỦA QUÁ TRÌNH HẤP THỤ TRONG PLASMA LASER

Torres-Silva, Trần Tuấn

TÓM TẮT: Vấn đề tương tác của một xung laser cực mạnh với trạng thái giả tự do của điện tử đã được khảo sát gần đây. Để đơn giản và tính gần đúng quá trình trao đổi năng lượng nhiều photon kèm theo sự tán xạ tương đối của hạt mang điện với tần số va chạm hiệu dụng đã được tìm thấy. Với những điều kiện cộng hưởng tuyến tính cổ điển không thể giải thích sự hấp thụ trong thực nghiệm plasma laser. Trong công trình này, khi vận tốc hấp thụ là độc lập với hàm phân bố ban đầu và chỉ phụ thuộc vào cường độ thông lượng photon, chúng ta chứng minh rằng hệ số hấp thụ hiệu dụng là tỉ lệ với I^r, ở đây r là thông số $0{,}5 \le r \le 0{,}75$. Thừa số tỉ lệ được so sánh bởi biểu thức Brunel và các kết quả nhận được từ thực nghiệm.

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