

## NONLINEAR ABSORPTION OF SUPERSTRONG CIRCULARLY POLARIZED LASER RADIATION IN PLASMA OWING TO INVERSE BREMSSTRAHLUNG ON COULOMB CENTERS

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**Abstract** – Nonlinear absorption of circularly polarized ultrastrong laser radiation in plasma through the induced bremsstrahlung of electrons on Coulomb centers in the scope of low-frequency approximation is investigated based on the numerical simulations. We study the cases of isotropic and anisotropic distributions of plasma electrons over the momenta and show that for both cases the coefficient of nonlinear absorption is inversely proportional to the wave intensity. Coefficient of nonlinear absorption of relativistic Maxwellian plasma at high temperatures of electrons is considered.

Key words: superstrong laser radiation, plasma, nonlinear absorption, Coulomb centers

The development of high-power laser systems with ultrashort pulse duration [1] has created an opportunity to generate plasmas under unique conditions that is very high electron densities and relativistic temperatures [2, 3]. One of the fundamental processes at the interaction of strong laser fields with plasma is stimulated bremsstrahlung (SB) of electrons on the ions/nuclei. Moreover, under some circumstances inverse SB may become dominant mechanism of absorption of strong electromagnetic (EM) radiation in the plasma.

The intensities of currently available ultrashort laser pulses may considerably exceed the relativistic values - if the energy of interaction of an electron with the field over a wavelength is of the order of the electron rest energy ( $10^{18} \text{ Wcm}^{-2}$  in the optical region or  $10^{16} \text{ Wcm}^{-2}$  in infrared region). The SB process for such intensities proceeds essentially through the multiphoton channels, and at the asymptotically large intensities when the dimensionless relativistic invariant parameter of intensity  $\xi = eF_0 / (m_e c \omega) \gg 1$  ( $e$  and  $m_e$  are the electron charge and mass,  $F_0$  and  $\omega$  are the electric field amplitude and frequency of a laser radiation,  $c$  is the light speed in vacuum) the absorption coefficient (AC) of a homogeneous electron beam exhibits unusual

dependence on the wave intensity ( $\approx 1/\xi^2$ ) [4]. The latter has been obtained for a monoenergetic electron beam, while from the point of view of current laser-plasma actual problems it is of great interest to study the nonlinear behavior of AC of relativistic Maxwellian plasma at high temperatures of electrons.

As in the strong EM wave field SB process has significantly multiphoton nature, the task can be considered in the scope of classic theory [5]. First the study of the absorption of strong radiation in fully ionized plasma in the SB process was performed on the basis of kinetic theory in [6]. In this paper we consider the dependence of plasma nonlinear absorption on the intensity of external radiation using exact analytical expressions [4] for absorption coefficient in low frequency (LF) approximation. In this approximation the elastic scattering on the potential  $U(r)$  takes place, and the instantaneous interaction of an electron with the scattering potential does not change the wave phase during the scattering process. This approximation is applicable if

$$\lambda \gg R_U, \quad (1)$$

where  $\lambda$  is the laser radiation wavelength and  $R_U$  the range of effective scattering.

Laser-assisted electron-ion collisions in the plasma have two important effects. First of all, they are responsible for the absorption of energy via inverse bremsstrahlung. Second, thermalization of particles' energy proceeds via collisions. In this paper, we have considered only the first effect. For the description of thermalization processes, one should solve self-consistent kinetic equations. The obtained results can be applied to the underdense plasma at  $\omega > \omega_p$ , as well as to the overdense plasma at  $\omega < \omega_p$  if one considers the interaction of the laser beam with ultrathin (comparable to skin depth) plasma targets of solid densities. In both cases, one should take into account the condition of applicability in the LF approximation (1), which for plasma reads

$$\lambda \gg \lambda_D, \quad (2)$$

where  $\lambda_D = k_B T / 4\pi n_e e^2 Z$  is the Debye screening length,  $k_B$  the Boltzmann constant,  $T$  the plasma temperature of electrons:

$$\lambda_D [cm] = 7.43 \times 10^2 \sqrt{\frac{T [eV]}{Z n_e [cm^{-3}]}}. \quad (3)$$

In the presence of a laser field, electron–ion binary collisions take place with the effective frequency  $\nu_{eff}$  [5]:

$$\nu_{eff} = \frac{p_0^2 \nu_0}{\langle p \rangle^2 \langle v \rangle} \nu_{ei}, \quad (4)$$

and field free collision frequency, defined by equation

$$\nu_{ei} = \frac{2\pi Z^2 e^4}{p_0^2 \nu_0} L_{cb}, \quad (5)$$

where  $L_{cb}$  is the Coulomb logarithm,  $p_0$ ,  $\nu_0$ , and  $\langle p \rangle$ ,  $\langle v \rangle$  are the initial and mean values of electron momentum and velocity in the laser field, respectively. During the time of the order of  $\nu_{eff}^{-1}$ , the thermalization of the electrons energy in plasma occurs; hence our consideration is valid if the laser pulse duration  $\tau$  is restricted by the relation

$$\tau < \nu_{eff}^{-1}. \quad (6)$$

Note that the last condition can be satisfied even at the solid densities ( $n_e \approx 10^{24} \text{ cm}^{-3}$ ) for superstrong laser fields  $\xi_0 > 1$  ( $v \rightarrow c$ ) and  $\tau < 200 \text{ fs}$ , which we consider in the present paper in numerical calculations.

At relativistic laser intensities  $\xi \approx 1$  (especially for  $\xi \gg 1$ ), as it has been shown in [4], the SB process is well enough described by the classical theory, in the low frequency approximation. Hence, the absorption coefficient  $\alpha$  for a radiation field of arbitrary intensity, in general case of the homogeneous ensemble of electrons with the arbitrary distribution function  $f(\vec{p})$  over relativistic momenta  $\vec{p}$ , at the inverse-bremsstrahlung on the scattering centers with concentration  $n_i$  can be represented in the form ( $\text{cm}^{-1}$ ):

$$\alpha = \frac{n_i}{2\pi I} \int f(\vec{p}) d\vec{p} \int_0^{2\pi} \frac{d}{dt} W(\vec{p}, \tau_0) d\tau_0 \quad \left( \int f(\vec{p}) d\vec{p} = N_e \right), \quad (7)$$

where  $n_i W$  is the classical energy absorbed by a single electron per unit time due to SB process on the Coulomb scattering centers;  $\tau_0$  is the scattering phase in the EM wave, and  $I = c|F_0|^2 / 4\pi$  is the wave intensity of circular polarization (the integration is performed over the initial phase  $\tau_0$ ).

We will investigate cases with significantly anisotropic Gaussian (over the momenta) and isotropic Maxwellian distributions of relativistic electrons in the plasma for relatively simple numerical calculations - in case of circularly polarized wave. Indeed, the wave polarization does not qualitatively change the main results of the work [4]. According to latter, the change of energy of one electron due to the scattering on Coulomb centers (in LF approximation) in the strong EM wave field of circular polarization with the vector potential:

$$\vec{A}(\tau) = A_0(\vec{e}_1 \cos(\tau) + \vec{e}_2 \sin(\tau)), \quad (8)$$

( $\vec{e}_1, \vec{e}_2$  are unit vectors;  $\vec{e}_1 \perp \vec{e}_2 \perp \vec{k}$ ,  $\tau$  is wave phase) at a certain phase  $\tau_0$  is given by the relation (taking into account the definitions  $\vec{p}_{0i} \equiv \vec{p}_{0i}(\tau_0)$ ,  $E_{0i} \equiv E_{0i}(\tau_0)$ ):

$$\begin{aligned} \frac{dW}{dt}(\vec{p}, \tau_0) = & 2\pi \frac{Z_a^2 e^5 m_e^2 c^2}{(\vec{n}\vec{p}')^2} \frac{E_0}{p_0^3} \left\{ \left( 1 + E_0 \frac{\vec{n}\vec{p}'}{m_e^2 c^3} \right) \left[ -\Lambda \cos(\tau_0 - \varphi(\vec{p})) - 4Z \right] \right. \\ & - 2Z \frac{\vec{p}_{0\perp}^2}{m_e^2 c^2} + \left. \left\{ \Lambda \cos(\tau_0 - \varphi(\vec{p})) + 2Z \left( 1 - E_0 \frac{\vec{n}\vec{p}'}{m_e^2 c^3} \right) \right\} \right. \\ & \left. \times \ln \left( 1 + E_0 \frac{\vec{n}\vec{p}'}{m_e^2 c^3} - \frac{c\vec{n}\vec{p}'}{\omega m_e^2 Z_a e^2} \frac{p_0^3}{E_0} \right) \right\}, \quad (9) \end{aligned}$$

where

$$E_0 = E + \Lambda \cos(\tau_0 - \varphi(\vec{p})) + 2Z, \quad \vec{p}_0 = \vec{p} - \frac{e\vec{A}(\tau_0)}{c} + \vec{n}c(\Lambda \cos(\tau_0 - \varphi(\vec{p})) + 2Z) \quad (10)$$

are the energy and momentum of an electron in the wave,  $\vec{p}' = \vec{p} - \vec{n}E/c$ . The parameters  $Z$ ,  $\Lambda$ ,  $\varphi$  have the form

$$Z = -e^2 A_0^2 / (4c^3 \vec{n}\vec{p}'), \quad \Lambda = eA_0 \sqrt{(\vec{p}\vec{e}_1)^2 + (\vec{p}\vec{e}_2)^2} / (c^2 \vec{n}\vec{p}'), \quad \varphi(\vec{p}) = \tan^{-1} \left( \frac{\vec{p}\vec{e}_2}{\vec{p}\vec{e}_1} \right). \quad (11)$$

In all numerical calculations for a wave frequency we assume  $\hbar\omega \approx 1 eV$ . The case of anisotropic plasma with monochromatic electron momentum distribution ( $f(\vec{p}) = n_e \delta(\vec{p} - \vec{p}_0)$ ) at a specific geometry of the electron beam has been considered in [4]. Performed numerical calculations allow us to explore the absorption coefficient in anisotropic plasma in a wide range of wave intensities and for arbitrary geometry of an electron beam.

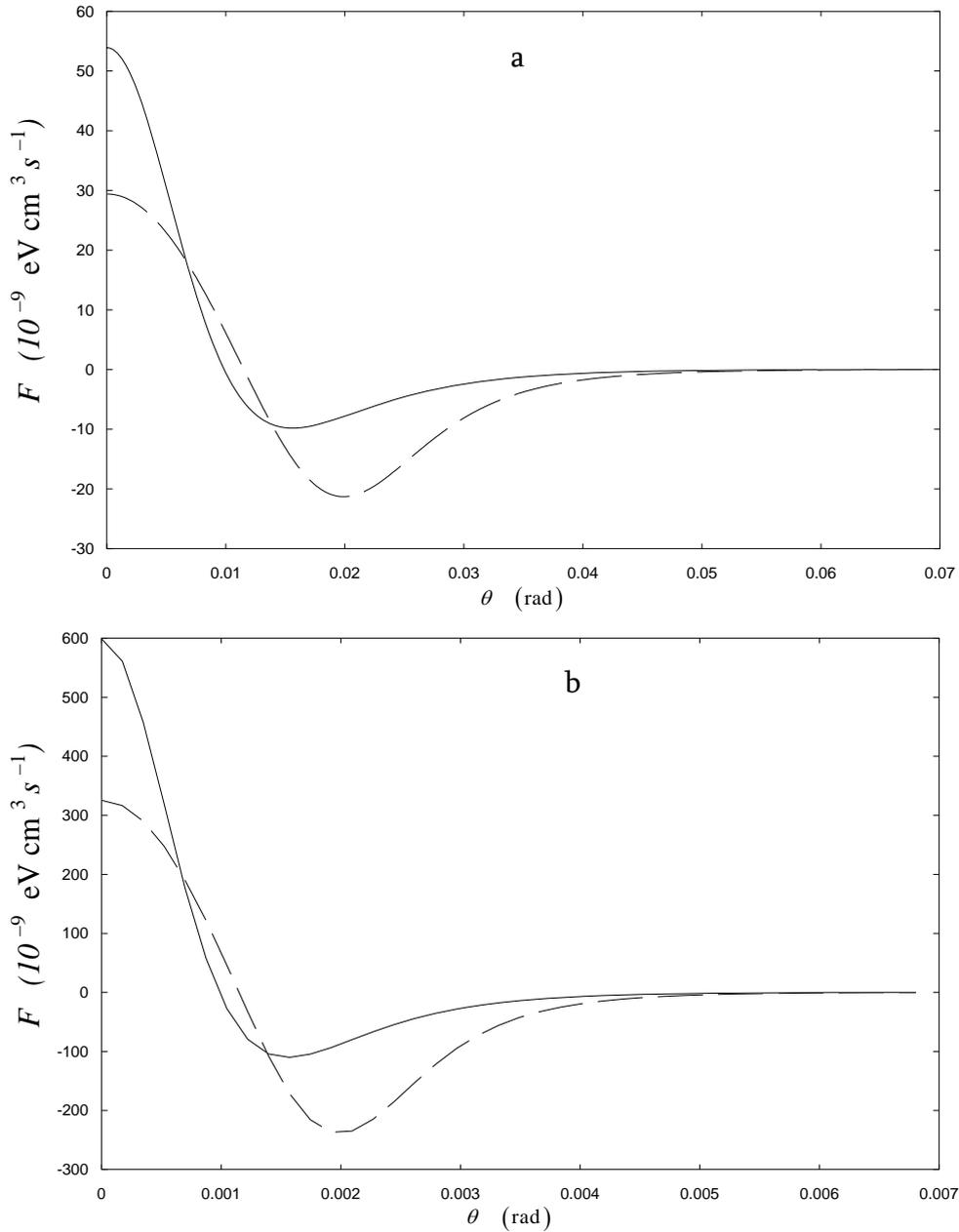


Fig. 1. Plots of  $F(\theta) = b\alpha$  ( $b = m^2 c^3 \omega^2 / 4\pi Z_a^2 e^2 n_i n_e$ ) as a function of the angle  $\theta$  between the directions of propagation of EM wave and electron beam with an initial energy  $E_0 = 270$  MeV (solid line) and  $E_0 = 27$  MeV (dashed line) with frequency  $\hbar\omega = 1$  eV for circularly polarized wave. In a) and b) intensity parameter values  $\xi = 0.1$  and  $\xi = 1$ , respectively.

To find out the angles of incidence of a relativistic electron beam at which the negative absorption is possible follows by the condition of plasma heating: Figure 1 illustrates the plots of the relation  $F(\theta) = b\alpha$  ( $b = m_e^2 c^3 \omega^2 / 4\pi Z_a^2 e^2 n_i n_e$ ) (by integrating expression for the absorption coefficient  $\alpha$  (2) numerically over the initial phase), where  $\theta$  is the angle between the vectors

$\vec{n}$  and  $\vec{p}$  for the electron beam with the initial energy  $E_0 = 270$  MeV (solid line) and  $E_0 = 27$  MeV (dashed line), respectively.

To investigate the dependence  $\alpha$  on the intensity of EM wave, Figure 1a and 1b show the dependence of  $F(\theta)$  for two values of the relativistic invariant intensity parameter of EM wave  $\xi = eA_0 / mc^2 = 0.1$  and  $\xi = 1$ . In both cases the absorption reach the maximum value when the electron beam is parallel to the wave propagation direction (vector  $\vec{n}$ ).

Figures 2a and 2b show the dependences of the wave absorption rate  $dW/dt = b\alpha\xi^2$  (with  $\alpha$  determined by (2), where the integration is performed over  $\theta$ ) on the intensity parameter  $\xi$ , for moderately relativistic ( $E_0 = 2.7$  keV) and relativistic ( $E_0 = 27$  MeV) beams, respectively. As it has been obtained in [4], absorption rate  $dW/dt = b\alpha\xi^2$  for EM wave of ultrahigh intensity  $\xi \gg \gamma$  in cases of both the nonrelativistic and relativistic electron beams is inversely proportional to the square of the wave electric field strength. As is seen, for moderately relativistic beam absorption rate has a peak at  $\xi \approx v_0/c$ , and at low intensity ( $\xi \ll 1$ ) of EM wave absorption by such a beam is more effective than by a relativistic one. For the relativistic beam there is not such a peak, but at high intensity ( $\xi \gg 1$ ) of EM wave the absorption is more effective by a relativistic beam.

Next we investigate the effect of the scatter through the factor  $\alpha$  (2). Since the magnitude of variation of the absolute value of the electron momentum is of the order of  $\Delta_p / p = \Delta_E / \gamma E$  ( $\gamma$  is the Lorentz factor), one can assume that for ultrarelativistic particles the energy spread is not important for  $\alpha$  (2). Our studies have shown that the taking into account the angular divergence  $\Delta_\theta$  of the beam also leads to insignificant amendments, so the consideration of a monoenergetic beam instead of a real one for SB process is justified, in contrast, for example, to stimulated Compton scattering type [7].

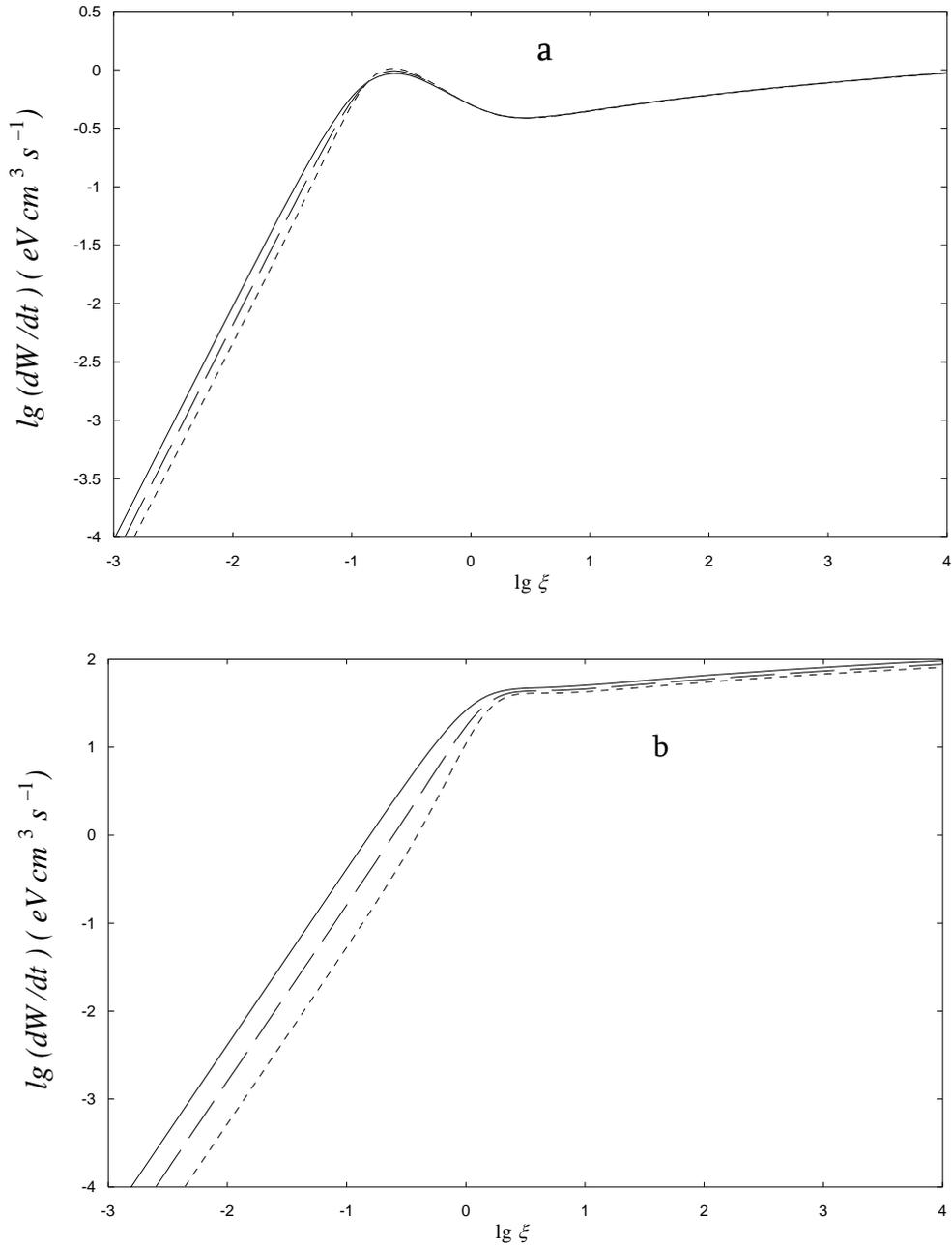


Fig. 2. Plots of logarithms from  $dW/dt = b\alpha\xi^2$  (7) ( $b = m^2c^3\omega^2/4\pi Z_a^2e^2n_i n_e$ ) as a function of the intensity parameter  $\xi$ , at the circular polarization of EMW with radiation frequency  $\hbar\omega = 1eV$ , for the electron beam with the initial energy: a)  $E_0 = 2.7$  keV and b)  $E_0 = 27$  MeV, respectively. In Fig. 2a electron beam momentum divergence width  $\Delta_{p_i} = 10^{-2}$  and angular divergence  $\Delta_\theta = 10^{-4}$  for  $\theta_0 = 0.17$  rad (solid line),  $\theta_0 = 0.34$  rad (dashed line),  $\theta_0 = 0.43$  rad (dotted line) and in Fig. 2b - for  $\theta_0 = 4$  mrad (solid line),  $\theta_0 = 6$  mrad (dashed line),  $\theta_0 = 9$  mrad (dotted line).

Let us represent the dependence of absorption rate  $dW/dt$  on the electron beam incidence angle  $\theta_0$ . For the beam momentum divergence width  $\Delta_p=10^{-2}$  and angular divergence  $\Delta_\theta=10^{-4}$ , according to the ratio  $dW/dt=b\alpha\xi^2$  with the AC  $\alpha$ :

$$\alpha = \frac{1}{2\pi J} \int f(p, \theta) dp d\theta \int_0^{2\pi} \frac{d}{dt} W(\vec{p}, \tau_0) d\tau_0, \quad (12)$$

and with a Gaussian distribution function (when  $\Delta_\theta \ll 1/\gamma$ ):

$$f(p, \theta) = \frac{n_e}{2\pi\Delta_\theta\Delta_p} \exp\left[-\frac{(p-p_0)^2}{2\Delta_p^2} - \frac{(\theta-\theta_0)^2}{2\Delta_\theta^2}\right], \quad (13)$$

in Figure 2a is represented the absorption rate for a moderately relativistic beam ( $E_0 = 2.7keV$ ) at  $\theta_0=0.17$  rad (solid line),  $\theta_0=0.34$  rad (dashed line),  $\theta_0=0.43$  rad (dotted line) and in Figure 2b for a relativistic beam ( $E_0 = 27MeV$ ) at  $\theta_0=4$  mrad (solid line),  $\theta_0=6$  mrad (dashed line),  $\theta_0=9$  mrad (dotted line), respectively. Integration over the initial phase  $\tau_0$  and  $\theta$  is carried out numerically.

Dependence is clearly visible at low intensity ( $\xi \ll 1$ ) of EM wave: the smaller the angle of incidence electron, the more efficient absorption of the radiation. At high intensity ( $\xi \gg 1$ ) of EM wave absorption of radiation does not depend on  $\theta_0$ .

Significantly different nature depending on the intensity of the absorption coefficient  $\alpha$  of a strong EM wave is obtained in the case of an isotropic distribution of plasma; the results are given in the logarithmic scale for relativistic Maxwellian distribution function for electron momentum (2):

$$f(\vec{p}) = \frac{n_e}{4\pi m_e^2 c k T K_2(m_e c^2 / k_B T)} \exp\left(-\frac{E(\vec{p})}{kT}\right), \quad (14)$$

( $K_2(x)$  is the Macdonald function,  $E(\vec{p}) = \sqrt{m_e^2 c^4 + \vec{p}^2 c^2}$ ) after numerical integration by phase  $\tau_0$  and the phase volume  $d\vec{p}$ .

To show the dependence of AC on the temperature of electrons in the relativistic plasma, in Fig. 3 the normalized AC - the function  $F_1(\xi, T)$ :

$$F_1(\xi, T) = (m^2 c^3 \omega^2 / 4\pi Z_a^2 e^2 n_i n_e) \alpha \quad (15)$$

is plotted for different intensities.

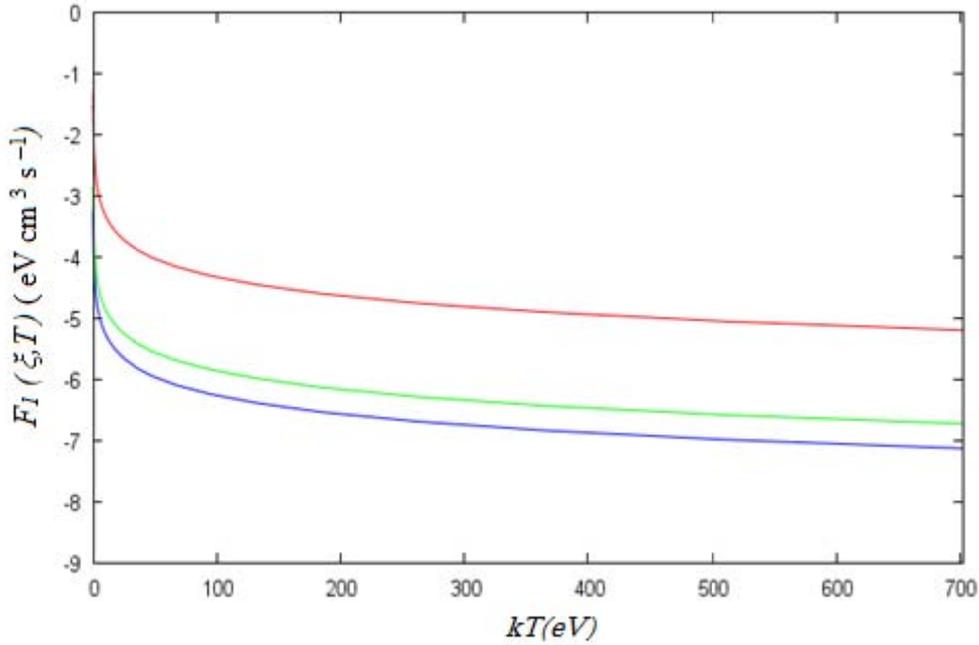


Fig 3. Nonlinear absorption coefficient: normalized AC versus  $kT$  for different laser intensities  $kT$  (eV):  $\xi = 1$  for red line,  $\xi = 6$  for green line, and  $\xi = 10$  for blue line.

In Fig. 4 shown the dependences of AC on the wave intensity: for convenience the function  $\xi^2 F_1(\xi, T)$  is plotted versus  $\xi$  for different plasma temperatures  $kT = 5.4eV$  (red line) and  $kT = 540eV$  (green line). If in the case of weak EM wave ( $\xi \ll 1$ ) isotropic distribution always leads to a positive absorption  $\alpha > 0$  (proportional to  $\xi^{-3}$  [2, 8]), at the transition to a strong EM wave ( $\xi \gg 1$ ) absorption coefficient remains positive, monotonically goes to zero in proportion to  $\xi^{-2}$  at the circular polarization of the laser field. Absorption is more efficient at the lower temperature of the plasma.

Summarizing, we can affirm that the current ultrashort pulse-lasers allow to investigate the nonlinear absorption coefficient of the plasma depending on the intensity parameter  $\xi$  in a wide range of values. In addition, for large values of  $\xi$  the absorption coefficient  $\alpha$  decreases as  $\xi^{-2}$  (for a circularly polarized EM wave) in contrast to the nonrelativistic case where one has the dependence  $\xi^{-3}$  [2]. The SB rate is suppressed with the increase of the plasma temperature but for the relativistic laser intensities it exhibits a tenuous dependence on the plasma temperature.

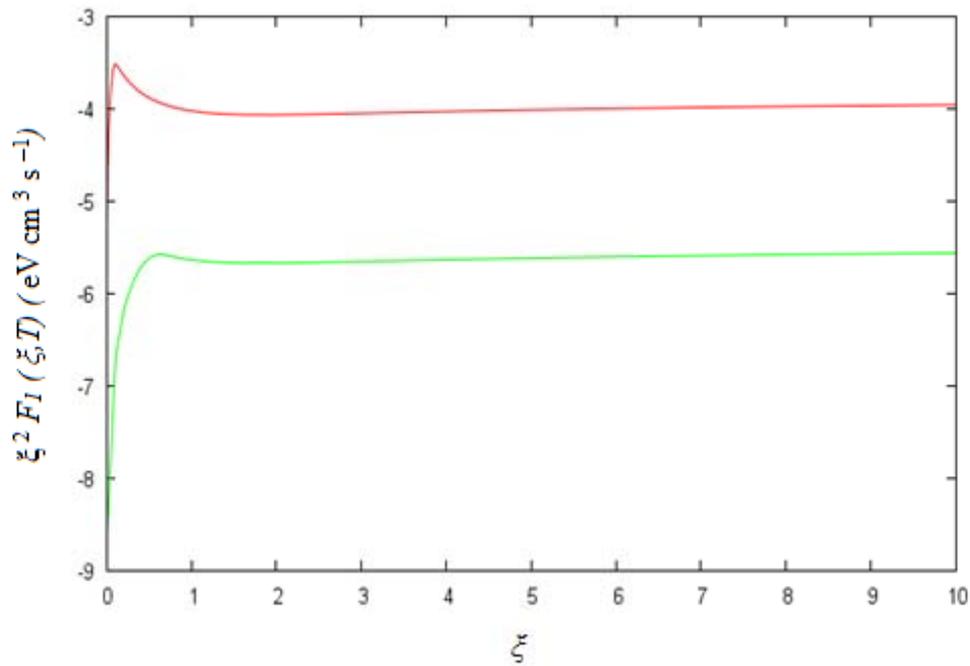


Fig. 4.  $\xi^2 F_1(\xi, T) = \left( m^2 c^3 \omega^2 / 4\pi Z_a^2 e^2 n_i n_e \right) \alpha \xi^2$  for isotropic Maxwellian plasma in the SB process as a function of  $\xi$  for the circular polarization of the laser field with frequency  $\hbar\omega = 1eV$ . Red line shows the dependence of AC for temperature  $kT = 0.2 a.u.$ , and green line for  $kT = 20 a.u.$ .

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