Response of strongly nonequilibrium plasma created by high power short UV laser pulse in rare gases to THz frequency band emission

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Abstract— **The response of plasma created by multiphoton gas ionization in an intense UV laser pulse to the terahertz frequency band radiation is studied. Analysis is based on the Boltzmann equation for the temporal behavior of the electron velocity distribution function (EVDF) in an arbitrary external electric field and allows to take into account both temporal retardation of the EVDF evolution with respect to the external electric field and the effect of the relaxation of the strongly nonequilibrium EVDF due to elastic electron - atomic collisions. The suggested theory enables to properly describe propagation of ultra-short THz pulses in laser plasma waveguides.**

I. INTRODUCTION

Recently, nonequilibrium plasma channels formed in gases characterized by an energy interval with an increasing transport cross section $\sigma_{tr}(\varepsilon)$ (for example, with a Ramsauer minimum) by a powerful femtosecond UV laser pulse were proposed for amplification of (sub)THz radiation [1]. Such amplification can be realized if the position of the peak in photoelectron spectrum is located in the range of positive derivative of the transport cross section over energy $d\sigma_{tr}/d\varepsilon$. It was demonstrated that for xenon plasma at atmospheric pressure it is possible to reach amplification of radiation with $\omega \le \nu \approx 10^{12}$ c^{-1} at the nanosecond time scale. To provide the amplification at frequencies of several THz one needs to use higher gas densities. The analysis of (sub)Thz pulse propagation and amplification [2] was restricted for quasi-monochromatic radiation with rather narrow spectrum only. In reality, THz pulses produced in modern experiments [3-6] are of several cycles of electric field oscillation and have wide spectrum that is beyond the study in [1,2].

In this paper we develop the analytical model for analyzing of electromagnetic response of strongly nonequilibrium and nonstationary plasma channel in rare gases that is beyond limitations on the duration of amplified THz pulses and their spectral width. The model is applied to study the possibility of amplification of THz pulses of ultrashort duration in relaxing xenon plasma formed by powerful femtosecond KrF pulse.

II. RESULTS

To calculate the response function we analyze the Boltzmann equation in two-term expansion for the EVDF in a plasma created by powerful femtosecond laser pulse:

$$f(\vec{v},t) = f_0(v,t) + f_1(v,t)\cos\theta \qquad (1)$$

Here the isotropic part of the distribution function $f_0(v,t)$ describes the electron distribution over absolute velocity value and initially is characterized by the narrow photoionization peak at $\varepsilon_0 \approx 2.87$ eV, while the small anisotropic part $f_1(v,t)$ allows one to calculate the electric current $j_z(t)$ arising in the plasma due to external electric field $E(t)$ of amplified THz pulse, directed along the z axis and θ is angle between the velocity vector and z axis:

$$j_z(t) = -\frac{4\pi}{3} e n_e \int v^3 f_1(v,t)dv = \int_0^t \sigma(\tau, t-\tau)E(t-\tau)d\tau. \qquad (2)$$

with the response function

$$\sigma(\tau, t-\tau) = \frac{4\pi e^2 n_e}{3m} \times \int v^3 \left(-\frac{\partial f_0(v,t-\tau)}{\partial v}\right)\exp(-\nu_{tr}(v)\tau)dv, \qquad (3)$$

where n_e is the electron density, $\nu_{tr} = N v \sigma_{tr}$ is the transport frequency, N is the gas density and σ_{tr} is the transport cross section. We see, that the dependence of electric current on time is rather complicated. It appears to be nonlocal in time: current at given instant of time depends on both electric field and EVDF $f_0(v,t)$ in all previous instants of time, i.e. retardation is pronounced. In the most simple case when $\nu_{tr} = \nu_0 = const$, taking into account that

$$\int v^3 \left(-\frac{\partial f_0(v,t-\tau)}{\partial v}\right) dv = \frac{3}{4\pi},$$

one obtains

$$\sigma(\tau, t-\tau) = \sigma_0(\tau) = {e^2 n_e}/{m} \times \exp(-\nu_0 \tau). \qquad (4)$$

First we note that in such situation the result does not depend on the type of expression for the symmetric part of the EVDF $f_0(v,t)$. Such a response function corresponds to the well-known plasma conductivity

$$\sigma_\omega = \int \sigma_0(\tau)\exp(i\omega\tau)\,d\tau = \frac{e^2 n_e}{m(\nu_0 - i\omega)}. \qquad (5)$$

and provides the absorption of the electromagnetic radiation of frequency ω in a plasma.

For the arbitrary dependence $\nu_{tr}(v)$ expression (3) can be rewritten in the form

$$\sigma(\tau, t-\tau) = \frac{4\pi e^2 n_e}{m} \times \int f_0(v, t-\tau) v^2 \left(1 - \frac{v\tau}{3}\frac{d\nu_{tr}(v)}{dv}\right)\exp(-\nu_{tr}(v)\tau)dv. \qquad (6)$$

We obtain, that the response function means the averaging of the expression over the EVDF at the retarded instant of time $t-\tau$. The most important is the fact that the sign of the expression under the integral can be different, both positive or negative in dependence of the sign and value of the derivative $d\nu_{tr}/dv$. Further we will make sure that negative values of $\sigma(\tau, t-\tau)$ can provide negative absorption (or amplification) of radiation in a plasma. Definitely, it is possible if the dependence $\nu_{tr}(v)$ is characterized by the energy interval with the positive derivative $d\nu_{tr}(v)/dv > 0$ while this energy interval contributes dominantly to integral (6). Necessary condition for amplification can be realized in the plasma

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channel formed by powerful UV laser pulse in gases characterized by the energy interval with increasing with energy transport cross section (xenon or krypton, nitrogen). In this case the photoelectron peak position should be located in the energy range where $d\sigma_{tr}/dv > 0$.

For the analysis of the response function we choose first the xenon plasma with the Maxwellian distribution. Transport cross section for xenon atoms was taken from [7]. Results of calculation of the response function in for different averaged over the EVDF energies $< \varepsilon >= (3/2)T$ (here T is the electronic temperature) are presented at Fig.1 (different average energies $< \varepsilon >$ are used as a second argument instead of retarded time). For the given parameters the "memory depth" is of order of several picoseconds. We should note that for Maxwellian distribution the response is positive in the whole range of parameters, hence plasma will absorb radiation.

Rather different situation appears to exist in strongly nonequlibrium plasma formed in gases by powerful femtosecond visible or UV laser pulses. In such a situation the photoelectron spectrum consists of one or several peaks corresponding to the multiphoton gas ionization. Plots of the response function for the EVDF with a single Gaussian peak with different energy position ($< \varepsilon >= 1 - 5$ eV) and the width of $\Delta\varepsilon = 0.1$ eV are presented at Fig. 2. Here electron average energy $< \varepsilon >$ is also used as a second argument instead of retarded time. The energy and temporal ranges of negative values of the $\sigma(\tau, < \varepsilon >)$ function are responsible for the possible amplification effect. In reality the effect of temporal retardation of the EVDF in eq.(6) becomes important if the EVDF is varying significantly in time during the THz pulse propagation. Such retardation can become of importance in Xe plasma, for example, at rather high electron densities when the electron-electron collisions should be taken into account. In this case the temporal evolution of $f_0(v, t)$ is much more faster and the relaxation of EVDF can be also of importance for analyzing of absorption/amplification of extremely short THz pulses.

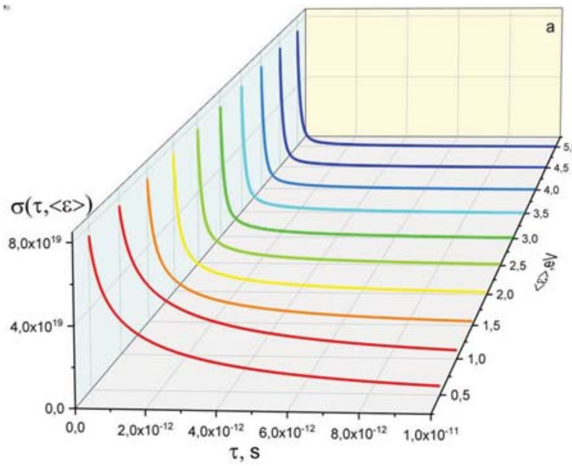

Fig. 1. The response function $\sigma(\tau, < \varepsilon >)$ for Maxwellian EVDF with average energy $< \varepsilon >= (3/2)T$ for xenon plasma. Electronic density is $3\ 10^{11}$ cm^{-3}, gas concentration is $3\ 10^{19}$ cm^{-3}.

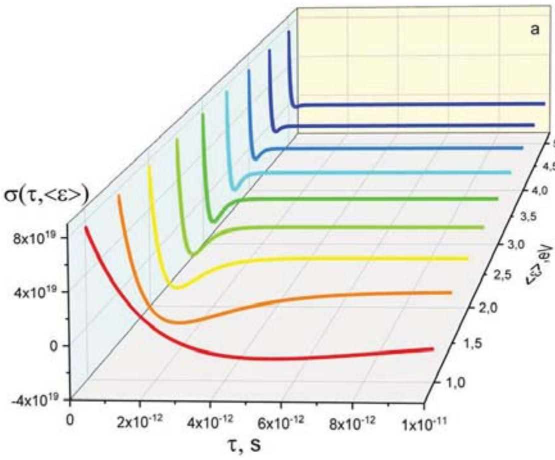

Fig. 2. The response function $\sigma(\tau, < \varepsilon >)$ for Gaussian peak EVDF at different peak positions for xenon plasma. Electronic density is $3\ 10^{11}$ cm^{-3}, gas concentration is $3\ 10^{19}$ cm^{-3}.

The possibility to amplify the THz radiation was found to be possible also in plasma channels in nitrogen (air) [8] as nitrogen molecules are also characterized with energy interval with growing transport cross section. In the case of nitrogen plasma relaxation of EVDF peak structure is much faster due to the excitation of vibrational states of N_2 molecules. As a result, only extremely short THz pulses (of one or two cycles) can be amplified.

III. Summary

Proposed model is highly suitable to be incorporated in the self-consistent analysis for short THz pulse propagation in a plasma channel based on joint solution of Boltzmann equation for EVDF in a plasma and wave equation beyond the paraxial approximation.

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