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Abstract

The general properties of ultra-short electromagnetic pulse (USP) interactions with highly charge ions in dense and high temperature plasmas are considered. The application of USP in X-ray spectral range provided by modern technology including free-electron laser machines opens up new opportunities for investigations of dense plasmas. They are based on the possibility of USP penetration into optically dense media due to their broad spectral distribution. In the framework of the use of USP for active spectroscopy in high energy density plasmas, new expressions of the transition probabilities are proposed. An aluminum plasma at local thermodynamic equilibrium is considered. The interaction of USP with hydrogen-like ions at $N_e=2\cdot10^{22}$ cm^{-3} and T=1 keV is analyzed in details by taking into account both the specificity of the USP and the plasma effects, such as Stark and Doppler effects on the line profile of the excited radiative transitions. The results are applied for demonstration of optical depth and pulse duration effects on excitation probabilities of the n=1 to n=3 radiative transition, which is the simplest atomic scheme to observe fluorescence signal.

Key words: ultra-short pulse, dense plasma, H-like ion excitation

1. Introduction

Studies of high energy density plasmas are of great interest as the latter occur widely in supernovae, in stellar interiors, in accretion disks, in plasma devices such as laser produced plasmas or Z-pinches and, in directly and indirectly driven inertial fusion experiments. The first means of studying plasmas is the analysis of their radiation. It is based on the comparison of observed and modeled spectra allowing to partially decrypt the hidden information. In particular, the determination of highly-charged ion contents in dense plasmas is usually based on passive measurements of radiation emitted by these ions excited by plasma electrons, see e.g. [1] and references therein. These methods of passive spectroscopy face with standard problems related to nonlocal nature of such measurements. The realization of active spectroscopy experiments, in which a pumping laser is used to selectively populate the atomic levels giving rise to a possible redistribution of the emitted radiation, would overcome this issue and would provide a major advance in the development of our understanding of spectral line formation, displacements of energy levels, radiation transfer and detailed process kinetics. Photo-pumping experiments, such as the ones, in which the helium-like aluminum spectral lines emitted by a laser-produced plasma were used to pump ground-state helium-like ions in another, spatially distinct, but more dense, aluminum plasma [2] or the monochromatic resonance-fluorescence experiments by using saturated X-ray lasers [3], have already been realized or proposed for high-Z plasma investigations. More recently, the combination of X-ray coherent radiation from free electron laser (XFEL) facilities, which succeed to reach photon energies up to several keV in femtosecond laser pulses [4], for plasma photo-pumping together with a high-powerful laser in the visible spectral-range for plasma generation, was proposed [5, 6]. The application of XFEL for investigations of dense laser-plasmas, makes it possible to excite plasma ions from their ground states resulting in great increase of excited level population. The observations of subsequent radiative transitions between excited atomic states, open a possibility of local observations of ions inside the plasma. One difficulty of this kind of experiments, is related to the penetration of resonant laser-radiation into optically thick dense plasmas. The original idea is to use wide band X-ray USP spectra in order to depress absorption and reach internal regions of the plasma. This can be realized by using a very bright photo-pumping source or by application of ultra-short electromagnetic pulses for excitation of atomic structures inside the plasma. The advantage of ultra-short pulses (USP) for diagnostics of optically thick media, is based on their possibility to penetrate into the medium due to their broad spectral distributions. The spectral width of USP is related to the inverse of their duration time. If this width is much broader than the absorption line widths of atoms in the absorbing medium, the pulse harmonics outside the range defined by the absorption line width around the absorption resonance will propagate inside the medium with small absorption. Thus the penetrating USP can excite atomic systems inside the optically thick medium. Then, the excited atoms can emit photons at radiative transitions different from optically trapped ones, making it possible the observation of the signal coming from the interior of optically thick medium. The modern USP production technique makes it possible to generate pulses in X-ray domain with very short pulse durations. In particular the pulse duration about several tens of attoseconds is already obtained [7]. According to recent LCLS data the fast development of XFEL laser facilities results in pulse shortening from 100 fs to 5 fs with nearest perspective for generation of 0.5 fs pulses [8]. New approach for USP generation by XFEL up to 10 as was proposed [9].

It is the goal of the present paper to look for possibilities of ion excitations inside optically thick hot dense plasmas using current and perspective X-ray pulses.

2. Spectral line shapes and penetration of USP into optically thick medium

Let us consider the penetration of USP into resonant optically thick medium. It means that the carrier frequency ω of the USP is close to radiative transition frequency ω_0 of ions in the plasma. The initial time-dependent form of USP is given by:

$$E(t) = E_0 \exp\left(-t^2/2\tau^2\right)\cos(\omega t + \varphi). \quad (1)$$

Where, E_0 is the electric field amplitude of the USP and τ is the pulse duration (the phase φ is of no importance for considerations below).

To find the transition probability, let us expand the field $E(t)$ into Fourier series. The square of such Fourier components determine the energy $J(\omega)$ per unit area, per unit frequency contained in the signal at frequency ω [10]:

$$J(\omega) = \frac{c}{4\pi^2}\left|E(\omega)\right|^2. \quad (2)$$

The intensity of the USP depends strongly on its penetration into a medium. Considering, for sake of simplicity, a one dimensional (along z axis) uniform absorbing plasma, the energy per unit area per unit frequency at the distance *L* from the plasma boundary is given by:

$$J(\omega, L) = J(\omega, z = 0)\exp(-k(\omega)L) \tag{3}$$

where, *k(ω)* is the absorption coefficient near a specific radiation frequency ω_0 close to a resonance transition of the ion spectrum.

$$k(\omega) = 2\,\pi\, N_0\, \lambda\!\!\!^{-2}\, A\, G(\omega) \tag{4}$$

where, N_0 is the ion density, $\lambda\!\!\!^{-} = \lambda/2\pi$, with λ the wavelength of radiative transition under consideration, *A* is the radiative decay rate of the transition under consideration, G(ω) is the corresponding line shape close to the carrier frequency of USP.

The absorption depends strongly on the structure of the line shape. In order to extract the line broadening parameters, let us write down the line shape as a function of dimensionless parameters:

$$G(\omega)d\omega = G(\beta)d\beta, \quad \beta = (\omega - \omega_0)/\Delta \tag{5}$$

where Δ is the effective line width of the line under consideration. In general case, the determination of the line-width is not arbitrary and is not straightforward. It depends on different broadening mechanisms responsible for the line shape formation in plasmas such as collisional electronic broadening, ionic Stark effect and Doppler effect. Modeling broadening due to Stark effect of transitions from neutral or charged emitters is a complicated problem that involves a complex combination of atomic physics data, statistical mechanics, and detailed plasma physics [11]. The most difficult part of a line-broadening problem is to properly and completely identify the environment of the radiator.

After substitution of the dimensional shape into eq. (3) one can express the penetration effect in terms of the optical thickness described by the standard equation:

$$\Lambda \approx k_0\, L \approx 2\pi\, N_0\, \lambda\!\!\!^{-2}\, L\, A/\Delta \tag{6}$$

where k_0 is absorption coefficient in the center of the line.

The key dimensionless parameters determining excitation probability in dense medium together with optical thickness (6) are defined as:

$$\beta = \frac{\omega' - \omega_0}{\Delta},\ \delta = \frac{\omega - \omega_0}{\Delta}, \alpha = \Delta\tau \tag{7}$$

where β is the dimensionless line shape frequency shift, δ is the detuning frequency shift between USP carrier frequency,ω and central frequency, ω_0 and α is the USP time duration parameter. Δ is the line-width, e.g. $\Delta \approx \mathrm{v}\,\omega_0 / c$ for Doppler or $\Delta \approx \mathrm{v}\, N\sigma$ for Lorenz, Stark or any other width following from numerical modeling, and ω' is the current frequency.

After having substituted the dimensionless parameters (6) and (7) into the general expression (2) for the attenuation of the pulse intensity, one obtains the expression of the spectral energy per unit area $J(\Lambda,\alpha,\beta,\delta)$ in the dense media:

$$J(\Lambda,\alpha,\beta,\delta)=\frac{c}{8\pi}\frac{E_0^2}{\Delta^2}\alpha^2\exp\left\{-(\beta+\delta)^2\alpha^2-\Lambda G(\beta)\right\}. \quad (8)$$

Before coming to specific calculations, let us estimate the values of dimensionless parameters entering in eq. (8).

For the typical example of Al^{+12} ion in dense plasma with parameters pointed above, the typical line width Δ is of the order of several electron-volts. Assuming the values of the wave length and radiative decay rate A equal to one for the Lyman-beta transition, one obtains an estimation of absorption coefficient k_0 being of the order of 10^3 cm^{-1}, which corresponds to an absorption length of the order of 10 μm that is typical for laser plasmas, see [1].

To find the spectral distribution of the energy per unit area according to eq. (8), one needs to calculate the spectral line shape for the radiative transition under consideration. The calculations were made by using the models and code described in the papers [12-14] accounting for ionic Stark broadening with ion dynamics and correlation effects, and electron and Doppler broadening. The result for the line shape is presented in the fig.1.

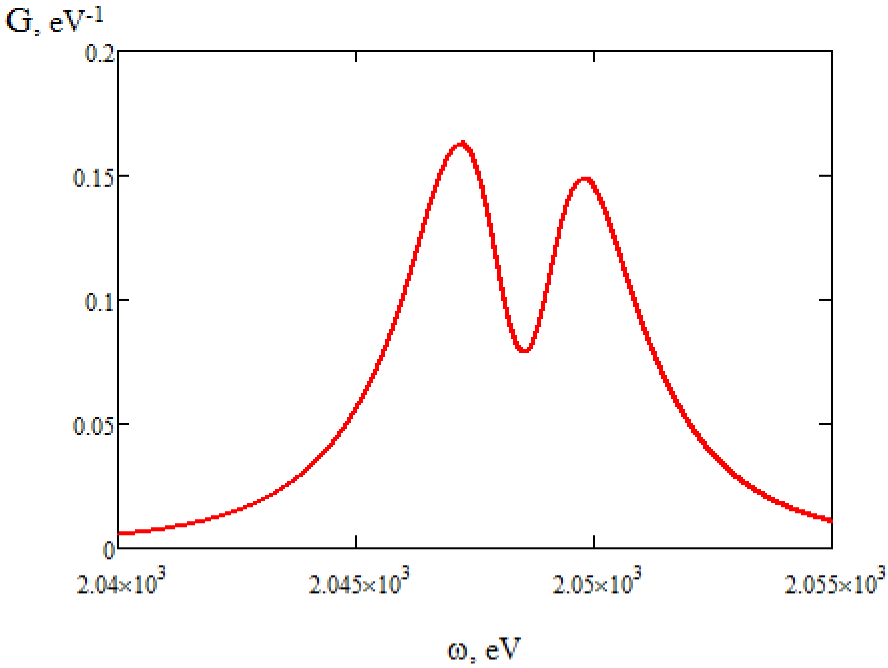

Fig.1. Line shape of Lyman-beta line of H-like Al ions in the laser plasma at T=1 keV, $N_e=2\cdot10^{22}cm^{-3}$

One can see that the ion broadening manifests itself by appearance of the dip in the central part of the Lyman-beta line. The typical line width is of the order of several electron-volts.

To determine the spectral energy per unit area, it is necessary to substitute the line shape (shown in Fig.1) in the general formula (8). The results are presented in the Fig.2 as a function of dimensionless frequency, β, and three values of optical depth, Λ=1, 10, 30. The pulse duration parameter is α=0.1, and the detuning parameter is chosen equal to zero.

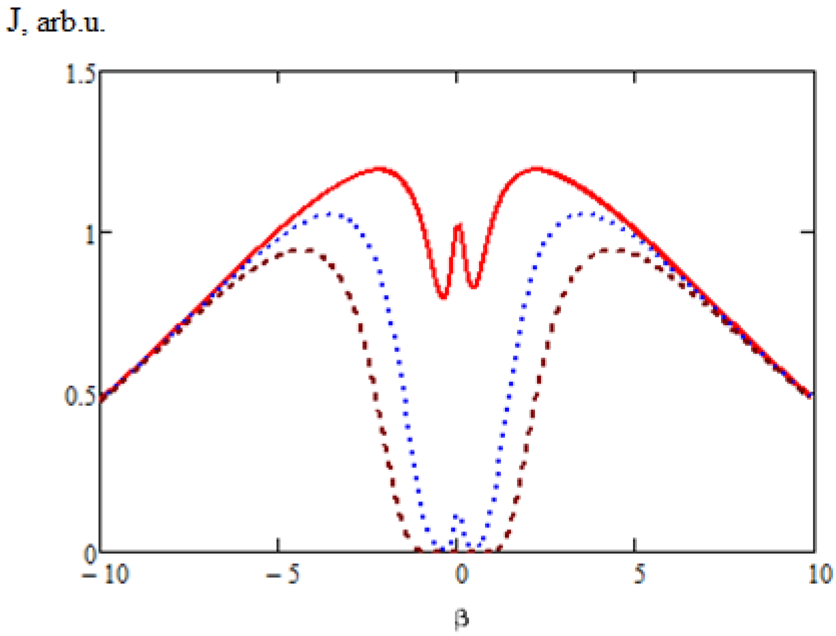

Fig.2: Spectral energy per unit area, J(Λ,α,β ,δ), for different values of optical depth: solid line – Λ=1, dotted line – 10, dashed line – 30 and pulse duration parameters α=0.1, δ=0.

One can see a deep minimum in the central part of pulse spectrum due to strong absorption in the central part of the spectrum, which increases with the increase of the optical depth. It follows from Fig.2 that the central dip observed in Fig.1 is noticeable on the shape of spectral energy per unit area at relatively small values of optical depth Λ=1, 10.

3. Excitations of Al H-like ions in laser plasmas.

The H-like and He-like ions of Al are popular objects for spectra observations in dense laser plasmas, see for example [1, 15]. Let us estimate the probability of such ion excitation by USP in laser plasmas with typical plasma parameters: T=1 keV, $N_e = 10^{22}$ cm^{-3}. The excitation probability of the transition from the ground state n=1 to the excited state n=3 corresponding to Lyman-beta radiative transition has been chosen. The transition has been selected as the simplest example of line excitation, which makes it possible to observe radiative transitions between excited states, which are not so strongly trapped as the radiative transitions to the ground state.
In the case of USPs containing only few optical cycles, the total excitation probability between atomic energy levels has a sense for the whole USP duration time. This is different from the standard case where one deals with the probability per unit time (Fermi “golden rule”). The transition to the standard case takes place for pulse duration large enough as compared with all relaxation parameters

Multiplying the spectral energy per unit area by the excitation cross-section and dividing it by the photon energy, one obtains the excitation probability by the specific harmonic. By integration over all harmonics (which corresponds to the integral over all Fourier frequencies) one gets the expression [16]:

$$W = \int_0^\infty \sigma(\omega') \frac{J(\omega')}{\hbar\,\omega'} d\omega' \tag{9}$$

Here σ is the excitation cross-section expressed in terms of spectral line shape of the radiative transition under consideration and $J(\omega)$ is the spectral energy per unit area considered in (2). Therefore, the general expression of excitation probability is expressed in terms of a convolution product of the USP shape and the spectral line shape. Note that the expression (9) has been obtained in the frame of the perturbation theory that means that the transition probability *W* has to be small compared to unity. Another important note is that the transition probability *W* is not proportional to the pulse duration; it is the case when the pulse duration goes to infinity and when one can use the standard probability per unit time; in general the dependence of the probability on pulse duration is essentially nonlinear (see below).
To find the expression for transition probability, one has to substitute the spectral energy per unit area (8) into general expression (9) resulting in:

$$W(\Lambda, \alpha, \delta) \propto \alpha^2 \int \exp\{-(\beta + \delta)^2 \alpha^2 - \Lambda\, G(\beta)\} G(\beta) d\beta\,. \tag{10}$$

The total probability depends on three dimensionless parameters, namely: the detuning parameter δ, the pulse duration parameter α and the optical depth Λ. The eq. (10) expresses the effect of medium optical depth in terms of universal parameters. Therefore, the same results can be obtained for different object following the same scaling parameters.

Let us estimate the range of physical parameters for specific case of Al plasma pointed above. By substitution of typical line width of order of 3 eV from fig.1, Lyman-betha line wave length and radiative decay rate for AlXIII ion, typical ion density 10^{21} cm^{-3} and plasma lengths of order of 10-100 μm one arrives to the optical depths Λ of order of 1-10. The typical pulse duration time is of the order of inverse line width being of the order of 0.3 fs. These ranges of plasma parameters are used below for specific calculations.

Figure 3 shows the effect of optical depth on the absorption probability for different pulse durations. Different electric field amplitudes have been chosen in order to make the probabilities equal for Λ=0. It is seen the strong effect of pulse duration on the absorption probabilities in optically dense media. It means that the absorption effects inside optically thick media are more effective by USP as compared with standard long pulses.

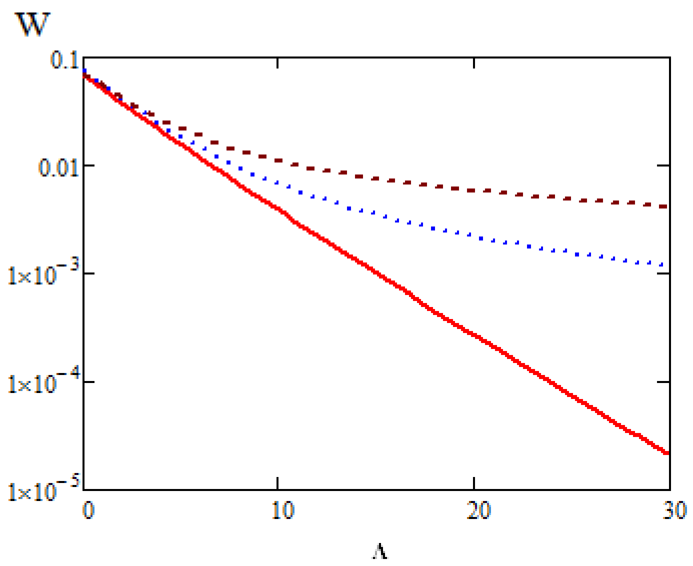

Fig.3: Effect of optical depth on the absorption probability for different pulse duration: α=5 – solid line, α=0.5 – dotted line, α=0.1 – dashed line, δ=0.

The effect of pulse duration α, on the transition probability *W* in laser plasma with different optical depths is shown in Fig.4. It is seen the essential influence of the optical depth on the increase of the transition probabilities.

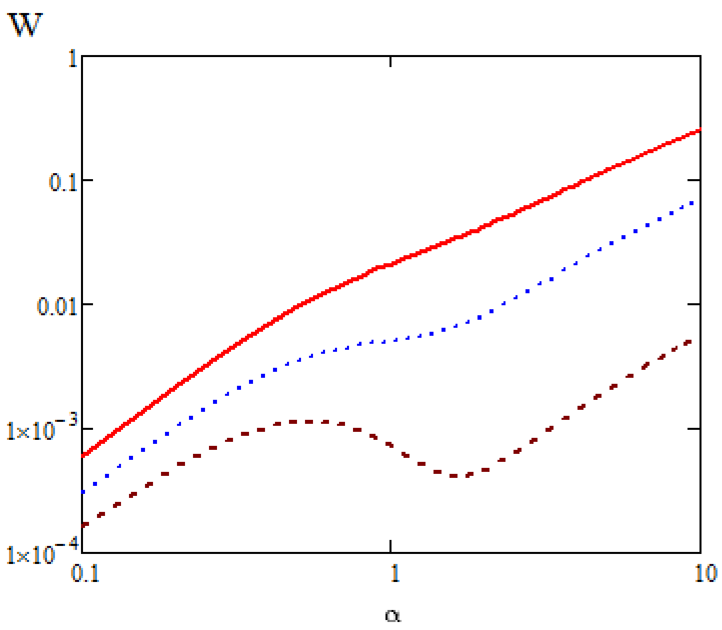

Fig.4. The effect of pulse duration on the transition probability for different optical depths: Λ=5 – solid line, Λ=10 – dotted line, Λ=20 – dashed line

It is seen nonlinear dependence of excitation probability on pulse duration especially for large values of optical depth.

4. Conclusion

The general properties of ultra short pulse interactions with highly charged ions in dense and high temperature plasmas have been considered. Plasma parameters typical for plasmas created by laser have been taken as examples. It has been shown that the effect of USP penetration into optically thick plasmas can be expressed in terms of universal dimensionless parameters, namely detuning frequency, time duration and optical depth of the medium. All these parameters are expressed in terms of the width of the intrinsic line profile in dense plasmas. The specific calculations of the Lyman-beta line shape of hydrogen-like Al^{+12} ion have been performed by using the PPP numerical code [10-12] taking into account the Stark broadening by ions and electrons, ion dynamics, as well as Doppler effect for realistic laser plasma parameters. The results have been applied for demonstration of excitation probability dependences on optical depth and pulse duration.

For specific example of Al plasma discussed above the pulse duration near 0.5 fs pointed in [8] is quite enough for observation of nonlinear dependences of the pulse absorption probability on pulse duration as it follows from fig.4. For longer XFEL pulses one need to deal with more sharp spectral line widths corresponding to lower density and temperature plasmas. It is to note that the problem of laser pulse penetration into optically dense media can be test not only for high density and temperature plasmas but for essentially lower plasma parameters typical for discharge plasmas using universal scaling low for pulse absorption following from eq. (10).

Of course the considerations above deal with simplified examples of uniform plasma parameters. Practically laser plasmas are usually strongly non-uniform and do not follow universal scaling parameters pointed above because ion density enters both in optical depth and line widths. But it makes sense to consider these effects for specific experimental condition. In conclusion, we point out that the application of USP in X-ray spectral range opens up new perspectives for investigations of dense plasmas due to possible excitation of atoms from their ground states and to high penetration of USP into optically thick media.

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