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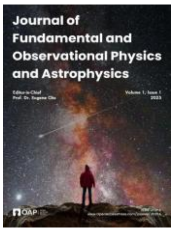

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Polarization Bremsstrahlung of quasi-classical electron induced by laser pulse

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ABSTRACT: The theory of polarization bremsstrahlung induced by an electromagnetic field is generalized to a pulsed laser field. The case of quasi-classical scattering of an electron on a multiply charged point-like ion with an electron core is considered. It is assumed that the carrier frequency of the laser pulse is in resonance with the natural frequency of the ion core. An expression is obtained for the probability of the photoprocess under consideration and its ratio to the probability of conventional bremsstrahlung induced by a monochromatic field is introduced. The dependences of this ratio on the carrier frequency and duration of the laser pulse are calculated and analyzed for various values of pulse amplitude.

KEY WORDS: polarization Bremsstrahlung effect; laser pulse; multicharged ion; quasi-classical electron; resonance polarizability.

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1. Introduction

The Bremsstrahlung effect induced by electromagnetic field(IBrS) involves the absorption/stimulated emission ofphoton/photons by an electron scattering on a target (atom/ion). This phenomenon is a fundamental radiative process, which is used, in particular, for plasma heating by laser radiation. There are two mechanisms of IBrS (as well as spontaneous Bremsstrahlung): the conventional mechanism, where the photon is absorbed/emitted directly by the scattered electron, and the polarization mechanism, where the interaction with radiation occurs through the target's electron core, and the field energy is absorbed/emitted by the incident electron.

IBrS in a monochromatic field has been studied in a number of works over the past several decades [1]. With the active development of laser pulse generation technology with controlled parameters [2], the study of IBrS in a pulsed electromagnetic field has become relevant.

This article aims to generalize the description of one-photon polarization IBrS [3] to the case of pulsed laser radiation

2. Basic formulas

The cross-section (relative to the electron flux) of one-photon polarization IBrS for the scattering of a quasi-classical electron on a multicharged ion with charge $Z >> 1$ and an electron core in a *monochromatic* field with frequency ω and amplitude F_0 , in the Kramers limit $\omega >> \omega_{Coul} = m\mathrm{v}^3 / Z e^2$ (*v, m* — electron velocity and mass), has the form [1]:

$$\sigma_{pol}^{(e)}(\omega) = \frac{4\sqrt{\pi}}{3\sqrt{3}} \left(\frac{e}{\hbar \mathrm{v}} \right)^2 \left| \alpha(\omega) \right|^2 F_0^2, \tag{1}$$

where $\alpha(\omega)$ is the dynamic polarizability of the target.

Below, we consider the resonant case when the laser radiation frequency is close to one of the natural transition frequencies in the ion's electron core $\omega \approx \omega_0$, ω_0 — the frequency of a dipole-allowed transition in the ion core. Taking into account the influence of the laser field on the electron transition in the core, the resonant polarizability of the ion is given by the following expression [4]:

$$\alpha(\omega, \Omega_0) \cong \left(\frac{e^2}{2m\omega} \right) f_0 \frac{\omega_0 - \omega + i\gamma}{(\omega_0 - \omega)^2 + \gamma^2 + \Omega_0^2}, \tag{2}$$

where f_0 is the oscillator strength of the transition, γ is the damping constant, and Ω_0 is the resonant Rabi frequency, defined as:

$$\Omega_0 = \sqrt{\frac{3 f_0}{2m\hbar\omega_0}} F_0. \tag{3}$$

Expression (1) is valid under the approximation of a point-like ion, where the penetration of the external electron into the electron core can be neglected. We also disregard possible spin-orbit splitting Δ_{FS} and Doppler broadening Δ_D of the resonant transition, assuming that the Rabi frequency is sufficiently large: $\Omega_0 >> \Delta_{FS}, \Delta_D$.

Substituting the resonant polarizability (2) into the cross-section (1), we obtain:

$$\sigma_{pol}^{(e)}(\omega)=\frac{4\sqrt{\pi}}{3\sqrt{3}}\left(\frac{Ze^3}{m\,\mathrm{v}\hbar\omega^2}\right)^2\left|\frac{f_0}{2Z}\frac{\omega(\omega_0-\omega+i\gamma)}{(\omega_0-\omega)^2+\gamma^2+\Omega_0^2}\right|^2 F_0^2. \tag{4}$$

The probability of the photo-process over the entire duration of the laser pulse can be represented as [5, 6]:

$$W=\int_0^\infty \sigma^{(ph)}(\omega)\frac{dN_{ph}}{d\omega dS}d\omega, \tag{5}$$

where

$$\frac{dN_{ph}}{d\omega dS}=\frac{c}{4\pi^2}\frac{|F(\omega,\tau)|^2}{\hbar\omega} \tag{6}$$

is the number of photons in the laser pulse within a given frequency interval *dω* passing through an area element *dS* over the entire pulse duration *τ*, and $F(\omega,\tau)$ is the Fourier transform of the electric field strength in the pulse.

Equation (5) includes the cross-section of the photo-process relative to the photon flux, which is related to the cross-section relative to the electron flux (1) by the following equality:

$$\sigma^{(ph)}(\omega)=\sigma^{(e)}(\omega)\frac{j_e}{j_{ph}}=\sigma^{(e)}(\omega)\frac{N_e\mathrm{v}}{cE_0^2}8\pi\hbar\,\omega, \tag{7}$$

where $j_{e,ph}$ are the electron and photon flux densities, respectively, and $N_e$is the electron concentration. Taking (7) into account, from (4) we obtain:

$$\sigma_{pol}^{(ph)}(\omega)=\frac{32}{3}\left(\frac{\pi}{3}\right)^{3/2}N_e\frac{e^6f_0^2}{4\hbar cm^2\mathrm{v}\omega}\frac{(\omega_0-\omega)^2+\gamma^2}{\left[(\omega_0-\omega)^2+\gamma^2+\Omega_0^2\right]^2}. \tag{8}$$

The energy absorbed as a result of the polarization channel of the bremsstrahlung effect is:

$$\Delta\mathrm{E}_{pol}(\tau)=\frac{c}{(2\pi)^2}\int_0^\infty\sigma_{pol}^{(ph)}(\omega)|F(\omega,\tau)|^2d\omega. \tag{9}$$

Equality (9) follows from formulas (5)–(6).

The expression for the energy absorbed through the conventional (static) channel of the Bremsstrahlung effect $\Delta\mathrm{E}_{ord}$ follows from (9) by replacing the polarization IBrS cross-section with the static IBrS cross-section, which under the considered approximations is equal to [1]:

$$\sigma_{ord}^{(ph)}(\omega)=\frac{32}{3}\left(\frac{\pi}{3}\right)^{3/2}N_eZ^2\frac{e^6}{\hbar cm^2\mathrm{v}\omega^3}. \tag{10}$$

We introduce a ratio that characterizes the role of the polarization channel and the finite duration of the laser pulse in the Bremsstrahlung effect over the entire pulse duration:

$$R(\tau,\omega_c)=\frac{\Delta E_{pol}(\tau,\omega_c)}{\Delta E_{ord}(\tau\to\infty,\omega_c)}, \tag{11}$$

where ω_c is the carrier frequency of the laser pulse. Taking the previous formulas into account, the ratio (11) becomes:

$$R(\tau,\omega_c)=\left(\frac{m}{Ze^2}\right)^2\frac{\omega_c^3\int_0^\infty|\alpha(\omega)|^2\,\omega\,|F(\omega,\tau,\omega_c)|^2d\omega}{\int_0^\infty|F(\omega,\tau,\omega_c)|^2d\omega}. \tag{12}$$

In the resonant case, equality (12), taking into account the expression for polarizability (2), can be rewritten as:

$$R(\tau,\omega_c)=\left(\frac{f_0}{2Z}\right)^2\frac{\omega_c^3\int_0^\infty\omega^{-1}\frac{(\omega_0-\omega)^2+\gamma^2}{\left[(\omega_0-\omega)^2+\gamma^2+\Omega_0^2\right]^2}|F(\omega,\tau,\omega_c)|^2\,d\omega}{\int_0^\infty|F(\omega,\tau,\omega_c)|^2d\omega}. \tag{13}$$

In the monochromatic limit $\tau\to\infty$, (13) yields:

$$R(\tau\to\infty,\omega_c)=\left(\frac{\omega_c f_0}{2Z}\right)^2\frac{(\omega_0-\omega_c)^2+\gamma^2}{\left[(\omega_0-\omega_c)^2+\gamma^2+\Omega_0^2\right]^2}. \tag{14}$$

3. Results and discussions

We apply the derived formulas to describe the resonant polarization Bremsstrahlung effect during the scattering of a quasi-classical electron on a lithium-like oxygen ion O^{5+}, induced by a laser pulse with duration τ and a carrier frequency close to the natural frequency of the electronic transition 2s→3p in the considered ion: $\omega_c\approx\omega_0\cong3.037$ atomic units (86.2 eV), $f_0=0.26$.

Note that there is a relationship between the plasma temperature and the charge number of the most abundant ion in the plasma: $T=0.025\,Z^2$. Based on this equality, it is easy to verify that for Z=5, the condition for the quasi-classical motion of the electron is satisfied: $\eta=Ze^2/\hbar\mathrm{v}\cong4.47>1$. The ratio of the radiation frequency to the Coulomb frequency is of the order of 10, so the Kramers approximation condition is satisfied. Thus, in the considered case, the criteria for the approximations under which the expression for the IBrS cross-section (1) is valid are met.

In atomic units, for the 2s→3p transition in the O^{5+}ion, the following relation holds:

$$\Omega_0=0.36\,F_0, \tag{15}$$

which follows from the definition of the Rabi frequency (3). Below, we consider a sufficiently strong laser field $F_0>0.01$ atomic units. Estimates show that in this case, the spin-orbit splitting of the *3p* level can be neglected, since for it, $\Delta_{FS}\approx4\cdot10^{-4}$ atomic units, and accordingly, $\Omega_0(F_0>0.01$ atomic units$)>>\Delta_{FS}$. The damping constant γ is set equal to the Einstein coefficient A_{3p2s} for the considered transition: $\gamma=A_{3p2s}\approx10^{-6}$ atomic units.

Using formula (13), we calculate the dependence of the ratio *R* on the carrier frequency, duration, and amplitude of a laser pulse with a Gaussian envelope. The calculation results are presented in Figs. 1–4.

Figures 1–2 show the dependencies of *R* on the carrier frequency for various pulse durations and amplitudes, as well as the case of a monochromatic laser field (14). It can be seen that for short pulses, there is no spectral dip at the natural frequency of the resonant transition, which appears as the duration increases, so that for τ = 24 fs, the spectral characteristic of the ratio (13) approaches the monochromatic limit (14).

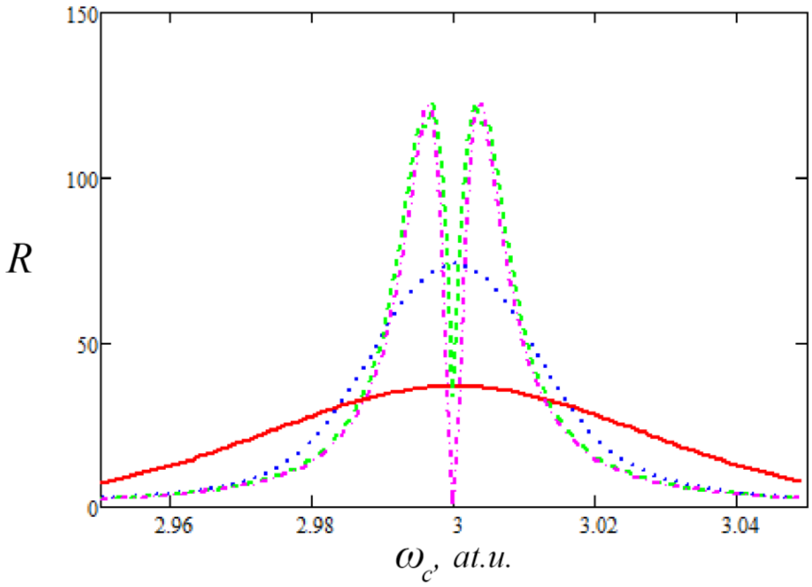

Figure 1. Dependence of the ratio *R* (formula (13)) on the carrier frequency of the laser pulse for various durations: solid curve — τ = 0.72 fs, dashed — τ = 2.4 fs, dotted curve — τ = 24 fs, dash-dotted curve corresponds to the monochromatic limit (14); electric field amplitude F0= 0.05 atomic units.

The presented dependencies show that in the near-resonant frequency region, the contribution of the polarization channel to IBrS dominates over the static contribution (*R* >>1) in point-like approximation for ion, except for a narrow interval near the natural transition frequency for long pulses.A comparison of Figs. 1 and 2 shows that as the amplitude of the laser pulse increases, the spectral dip deepens, and the side maxima spread apart. The latter follows from the form of the resonant polarizability in a strong field (2).

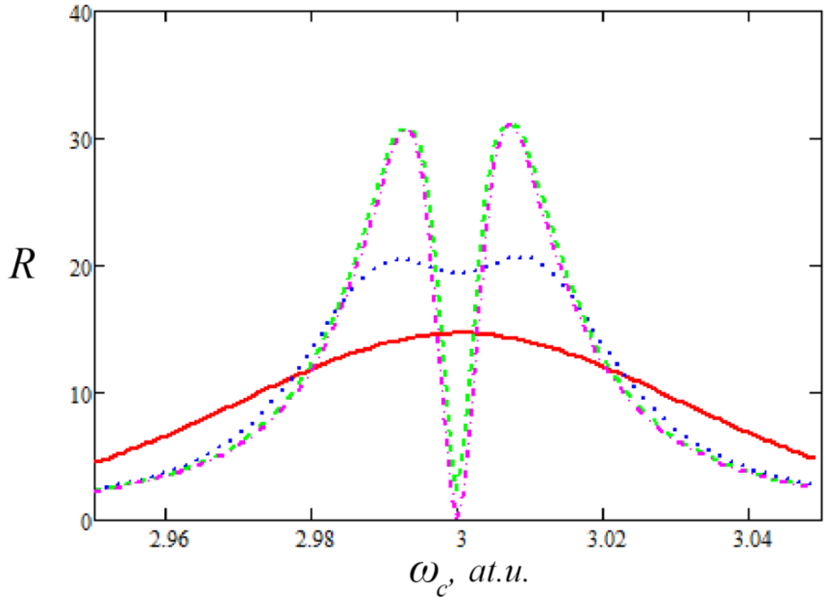

Figure 2. The same as in Fig. 1, for F0=0.1 atomic units.

Figures 3–4 show the dependencies of the energy ratio *R* on the pulse duration for various carrier frequencies and pulse amplitudes. It can be seen that for a relatively large detuning of the carrier frequency from the natural frequency of the resonant transition, these dependencies exhibit a maximum, which shifts toward shorter durations as the frequency detuning increases. Moreover, with an increase in the laser pulse amplitude (Fig. 4), a maximum in the dependence $R(\tau)$ also appears for the resonant carrier frequency $\omega_c=\omega_0=3$ atomic units, while for $\omega_c=3.02$ atomic units, the maximum smoothens out.

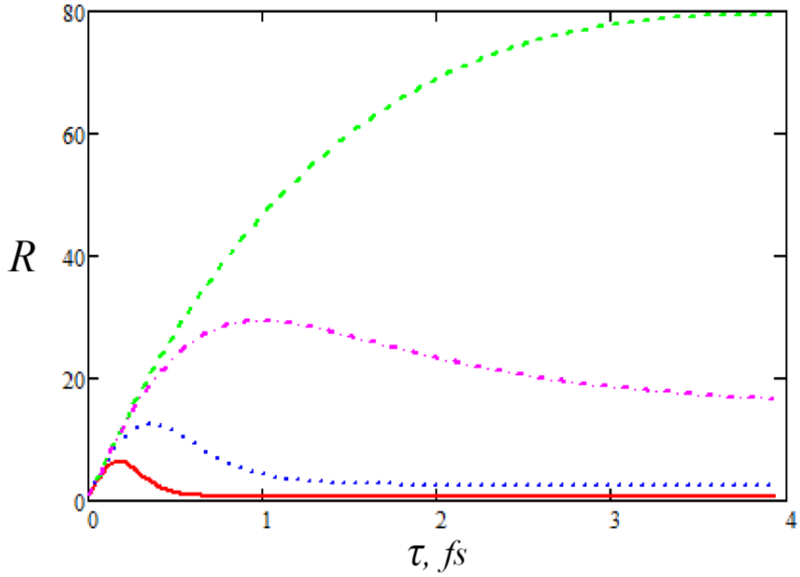

Figure 3. Dependence of the ratio *R* (formula (13)) on the duration of the laser pulse for various carrier frequencies: solid curve –ωc=2.9 atomic units, dashed –ωc=2.95 atomic units, dotted curve – ωc=ω0=3 atomic units, dash-dotted – ωc=3.02 atomic units; electric field amplitude F0=0.05 atomic units.

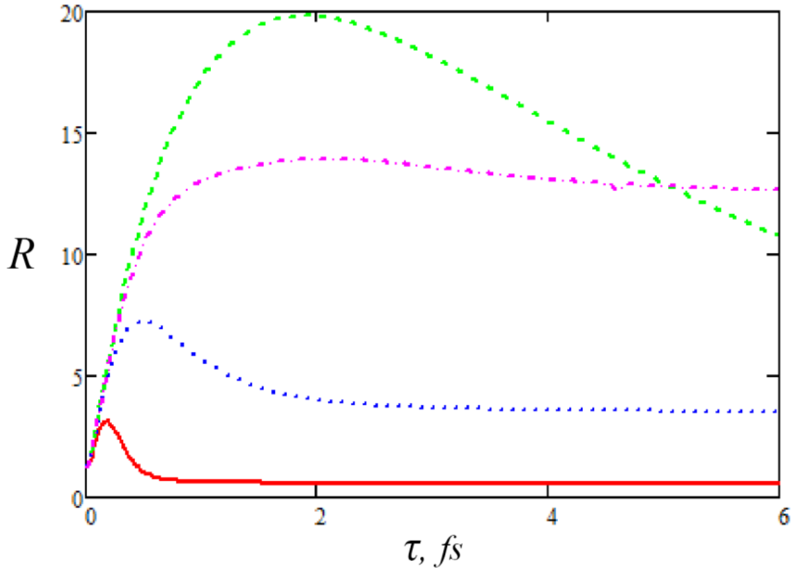

Figure 4. The same as in Fig. 3, for F0=0.1 atomic units.

4. Conclusions

Thus, using the derived expressions describing the polarization Bremsstrahlung effect in the field of laser pulse, its specific features distinguishing it from the analogous process in a monochromatic electromagnetic field have been established.In particular, it is shown that the dependence of the function $R(\tau)$, which characterizes the contribution of the polarization channel to the overall effect and the influence of the finiteness of the laser pulse on the process, has a maximum in the case of detuning of the carrier frequency of the pulse from resonance.

The consideration given in the article is generally valid for other ions and electron transitions, if the resonance condition is satisfied. Note that in the case of a resonance transition within an electron shell with a given principal quantum number, it will also be necessary to take into account the fine splitting of the p-state.

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