Spatio-temporal evolution of two-plasmon decay in homogeneous plasma

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Abstract. A hydrodynamic model of two-plasmon decay in a homogeneous plasma slab near the quarter-critical density is utilized to study the spatio-temporal evolution of the daughter electron plasma waves in plasma in the course of the instability. The influence of laser and plasma parameters on the evolution of the amplitudes of the participating waves is discussed, assuming that the secondary coupling of two daughter electron plasma waves with an ion-acoustic wave is the principal mechanism of saturation of the instability. The impact of inherently non-resonant nature of this secondary coupling on the development of TPD is investigated for the first time and it is shown to significantly influence the electron plasma wave dynamics. Its inclusion leads to non-uniformity of the spatial profile of the instability and causes the burst-like pattern of the instability development, which should result in the burst-like hot-electron production in homogeneous plasma.

1. Introduction

Two-plasmon decay (TPD) is a nonlinear parametric instability during which a large-amplitude electromagnetic pump wave decays into two electron plasma waves (plasmons) near the quarter-critical plasma density \[ n_{cr}/4 \]. It has been drawing considerable attention of both theoretical and experimental researchers for over four decades, ever since the work of Goldman [3]. This lasting interest for TPD, as well as for the whole class of three-wave parametric instabilities, is caused by their common occurrence in laser-plasma fusion experiments. TPD has primarily been known for its detrimental aspect, as a source of suprathermal (hot) electrons capable of preheating the fusion targets in the inertial confinement fusion setups [4–6]. Some recent experiments performed with multiple laser beams in planar geometry [6] suggest that the fractional preheat level, i.e., preheat energy normalized to incident laser energy, does not exceed 0.1% for laser intensities around \( 10^{15} \text{ W cm}^{-2} \). This is rather encouraging when the direct-drive experiments in National Ignition Facility (NIF) are concerned, although the notorious robustness [7] of the instability remains one of the major concerns of the researchers.

The initial, linear phase of TPD in homogeneous, as well as in inhomogeneous plasma has been studied extensively during recent decades, both theoretically and experimentally [8–17]. As a result of this, fairly correct concepts of the linear growth rate, homogeneous and inhomogeneous instability thresholds and other linear features of TPD have been developed. However, numerous questions concerning the
nonlinear nature of the instability need further study, among which its nonlinear saturation stands for a prominent example. Furthermore, the direct measurement of plasma density fluctuations in the course of the interaction, based on Thomson scattering, is available only in the experiments with CO₂ irradiations of rather cold preformed plasmas, in the regime \((v_0/v_e)^2 > 10\), where \(v_0\) is the electron quiver velocity and \(v_e\) stands for the electron thermal velocity which corresponds to the electron temperature \(T_e\) [2]. On the other hand, in experiments with visible and UV lasers interacting with plasma, in the \((v_0/v_e) \leq 0.1\) regime which is typical of most laser irradiations of interest to laser fusion, experimental verification of various aspects of the theory of TPD is rather difficult, and the comparison of theoretical and numerical predictions with the experimental evidence is mainly qualitative. Consequently, the importance of adequate numerical modeling in describing the instability dynamics in this regime is obvious.

In this context, the main goal of this paper is to shed more light on the spatio-temporal evolution of the amplitudes of the waves participating in the instability, especially the daughter electron plasma waves, and to study its dependence on the pump laser intensity and plasma parameters. Since the secondary coupling of the daughter electron plasma waves with ion-acoustic waves is widely recognized as the principal mechanism leading to the saturation of the instability, we are particularly interested in investigating the influence of the non-resonant nature of this secondary coupling on the wave dynamics and the spatio-temporal development of TPD. A transparent hydrodynamic model of TPD in spatially homogeneous plasma slab near the quarter-critical density is constructed, taking into account numerous nonlinear features of the instability. Similar model has been utilized earlier [18] in order to search for the time-dependent local solutions for the slowly varying wave amplitudes, by neglecting all the convective terms and, consequently, group velocities of the coupled waves in the corresponding coupled-wave equations, which was justified by the fact that the nature of the instability is strictly resonant. In present paper, we generalize this approach by simulating the complete set of coupled-wave equations numerically, in order to gain a more complete insight into the spatio-temporal behavior of the wave amplitudes inside the homogeneous plasma slab.

The paper is organized in the following fashion. In Section 2, we introduce the theoretical model that describes the evolution of the slowly varying amplitudes of the waves taking part in the development and the saturation of the instability in the homogeneous plasma slab. The model hydrodynamic equations are simulated using the appropriate numerical scheme and the corresponding results are presented and discussed in Section 3. Finally, Section 4 presents a brief summary and conclusions.

2. Theoretical model
Let us consider the propagation of a linearly polarized high intensity laser radiation (pump wave), with frequency \(\omega_0\) and wavelength \(\lambda_0\), in a homogeneous under dense plasma slab whose width is \(L = 100\lambda_0\). The pump wave enters the slab perpendicularly through its left boundary. If plasma density is in the vicinity of \(n_e/4\), the pump electromagnetic wave decays nonlinearly into two daughter electron plasma waves, whose frequencies and wave vectors are \(\omega_{1,2}\) and \(\vec{k}_{1,2}\), respectively. Resonant nature of TPD implies that the well-known matching conditions for the frequencies and wave vectors, \(\omega_0 = \omega_1 + \omega_2\) and \(\vec{k}_0 = \vec{k}_1 + \vec{k}_2\), must be satisfied strictly. Bearing in mind that the plasmon frequencies are temperature-dependant
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through the Bohm–Gross dispersion relations \( \omega_{1,2}^2 = \omega_{pe}^2 + 3k_{1,2}^2v_{e,1,2}^2 \), where \( \omega_{pe} \) is the electron plasma frequency and \( v_{e,1,2} \) are the corresponding thermal velocities, it is clear that the plasma slab density must be somewhat lower than \( n_{cr}/4 \) in order to provide conditions necessary for the onset of TPD.

An important item in the ongoing investigations of TPD instability is the mechanisms leading to its growth saturation. Numerous theoretical, experimental and simulation studies [9, 10, 19–22] have indicated that an efficient coupling of the plasma wave electrostatic energy to shorter wavelength ion density fluctuations, or ion-acoustic waves, is the main factor responsible for the saturation of the instability in homogeneous plasma. Our simulations performed in the limit of time-only dependence [18] confirmed that the saturation occurs simultaneously with the ion fluctuation amplitude reaching its maximum value, whose order was only a fraction of a percent of the bulk plasma density. The matching conditions for the secondary coupling are \( \omega_s = \omega_1 - \omega_2 \) and \( \vec{k}_s = \vec{k}_1 - \vec{k}_2 \), where \( \omega_s \) and \( \vec{k}_s \) are the frequency and the wave vector of the ion-acoustic wave. Since TPD excites a wide \( k \)-spectrum, the nature of the secondary coupling being clearly non-resonant, the corresponding frequency mismatch \( \Delta \omega = \omega_2 + \omega_s - \omega_1 \) must be taken into account when writing down the equations of the system evolution. Our earlier work [18] confirms that it leads to shifting and broadening of the frequency lines in the plasmon spectra, as well as an increase of their complexity and the appearance of new spectral lines corresponding to lower frequency oscillations. As we shall see, the influence of non-resonance of the secondary coupling on the saturation of the instability, and consequently on the spatio-temporal evolution of TPD, is significant and allows for a better understanding of some important features of wave dynamics. Although the inclusion of the frequency mismatch is a common feature in numerous models of parametric decay processes, to our knowledge it has never been done in this context before.

We start with the basic set of electron and ion fluid equations combined with the Maxwell equations, to yield the following system of normalized partial differential equations for the slowly varying amplitudes of the coupled waves, namely electromagnetic wave (\( a \)), electron plasma waves (\( N_1, N_2 \)), and the ion-acoustic wave (\( N_s \)) participating in the secondary coupling:

\[
\left( \frac{\partial}{\partial t} + V_0 \frac{\partial}{\partial x} \right) a = -B_0 N_1 N_2, \tag{1}
\]

\[
\left( \frac{\partial}{\partial t} + V_1 \frac{\partial}{\partial x} \right) N_1 = B_1 a N_2^* + C_1 N_2 N_s \exp(-i\Omega t) - \Gamma_1 N_1, \tag{2}
\]

\[
\left( \frac{\partial}{\partial t} + V_2 \frac{\partial}{\partial x} \right) N_2 = B_2 a N_1^* - C_2 N_1 N_s^* \exp(i\Omega t) - \Gamma_2 N_2, \tag{3}
\]

\[
\left( \frac{\partial}{\partial t} + V_s \frac{\partial}{\partial x} \right) N_s = C_3 N_1 N_2^* \exp(i\Omega t). \tag{4}
\]

Here, only the wave amplitude dependences in the direction of the pump propagation are accounted for, so the group velocities \( V_0, V_1, V_2 \) and \( V_s \) stand for the longitudinal components of the corresponding vectors. This can be done without loss in generality in the regime of prime interest for laser fusion applications, \((v_0/v_e) \leqslant 0.1\), where the transverse components of plasma waves are quite small, which is the case when
visible and UV lasers are utilized. From the geometry of the instability follows that in such cases one plasma wave is directed forward, almost along the x-axis, while the other is directed backward, and longitudinal components of their wave numbers relate as \(k_1 \sim k_0 \gg k_2\). All our simulation results refer to this parametric range, although even in the regime \((v_0/v_e)^2 > 10\), typical for CO2 laser driven plasmas, some interesting and qualitatively accurate predictions can be made.

In the system of equations (1)–(4), the time and space variables are normalized to \(1/\omega_0\) and \(c/\omega_0\) respectively, the group velocities of all the waves to the speed of light \(c\), and the frequency mismatch is normalized as \(\Omega = \Delta\omega/\omega_0\). The amplitude of the electromagnetic wave is represented by the dimensionless parameter \(a = v_0/c\). The amplitudes of the electrostatic waves are normalized to the equilibrium (bulk) plasma density \(n_0\), and the damping rates for the electron plasma waves, \(\Gamma_{1,2}\), which include both collisional and non-collisional (Landau) damping, to \(\omega_0\). The expressions for both damping terms can be found, for example, in Ref. [1], equations (5.26) and (9.18). The coupling coefficients are given as

\[
B_0 = \alpha^2 \kappa_\perp (\kappa_1^2 - \kappa_2^2) / 4k_1^2k_2^2, \\
B_{1,2} = \kappa_\perp (\kappa_1^2 - \kappa_2^2) / 8\kappa_{2,1}^2, \\
C_{1,2} = \alpha^3 |\vec{k}_1 \cdot \vec{k}_2| / 4\beta_e^2k_{2,1}^2k_s^2, \\
C_3 = \sqrt{Zm/M_i\beta_e^3} |\vec{k}_1 \cdot \vec{k}_2| / 4k_1^2k_2^2,
\]

and the dimensionless plasma parameters are \(\alpha = \omega_p/\omega_0 = \sqrt{n_0/n_{cr}}\) and \(\beta_e = v_e/c = \sqrt{T_e(\text{keV})/511}\). The value for the electron-ion mass ratio is taken to be \(Zm/M_i = 1/3600\) in our simulations, and all the wave vectors and their components are normalized to \(\omega_0/c\).

We will limit our discussion to the optimal case of maximum instability increment, since the contribution of the non-resonant coupling is relatively small due to the fact that TPD is an instability of highly resonant nature. The relation between longitudinal and transversal components of the wave vectors of daughter electron plasma waves in the case of maximum instability increment is the well-known equation of hyperbola \(k_\perp^2 = k_||^2 (k_|| - k_0)\). By combining this equation with the matching conditions for the onset of TPD and the dispersion relations for the electron plasma waves, and subsequently normalizing all the corresponding variables as stated above, we easily obtain the expressions for intensities of the normalized wave vectors of both electron plasma waves and their longitudinal and transverse components in the form

\[
\kappa_{1,2} = \sqrt{(1 - 2\alpha)/6\beta_e^2 \pm \sqrt{(1 - \alpha^2)(1 - 2\alpha)/12\beta_e^2}}, \\
\kappa_{1,2||} = \sqrt{(1 - \alpha^2)/4 \pm \sqrt{(1 - 2\alpha)/12\beta_e^2}}, \\
\kappa_\perp = \sqrt{(1 - 2\alpha)/12\beta_e^2} - (1 - \alpha^2)/4,
\]

while normalized intensity of the wave number of the ion-acoustic wave is

\[
\kappa_s = |\vec{k}_1 - \vec{k}_2|.
\]
Finally, longitudinal components of the group velocities, calculated from the corresponding dispersion relations and normalized to the speed of light, can be written in our notation as:

\[ V_0 = \sqrt{1 - \alpha^2}, \]

\[ V_{1,2} = (3\beta_e^2/2\alpha)(\sqrt{1 - 2\alpha/3\beta_e^2} \pm \sqrt{1 - \alpha^2}), \]

\[ V_s = \beta_e (\kappa_1 \kappa_2)/60\kappa_s. \] (9)

Clearly, the wave vectors and the scattering angles for the optimal case of maximum instability increment at given plasma density, as well as the group velocities of the participating waves, depend solely on the plasma parameters, \( \alpha \) and \( \beta_e \). Note that the relation (7) imposes the plasma temperature limit for the occurrence of TPD instability at given plasma density, as a consequence of the matching conditions for the frequencies and wave vectors, under the conditions specified by our model: \( T_e (\text{keV}) \leq 170.33(1 - 2\sqrt{n_0/n_{cr}})/(1 - n_0/n_{cr}) \). This temperature limit is above 4.5 keV for \( n_0 = 0.240n_{cr} \), which is not overly strict, but for \( n_0 = 0.248n_{cr} \) maximum plasma temperature is slightly above 0.9 keV.

The flexibility of this simple hydrodynamic model will allow us to pinpoint some important effects, usually masked in a more complex setting, which can later be taken into account in a more general context.

3. Results and discussion

Our first task is to simulate the system of equations (1)–(4) in the case of perfectly resonant secondary coupling \( (\Omega = 0) \), for a number of combinations of laser and plasma parameters and for varying distances from the left (entry) boundary of the plasma slab, in order to gain insight into the time evolution of the wave amplitudes during the process of TPD. We are particularly interested in the behavior of the shorter wavelength, forward propagating electron plasma wave, whose potential detrimental impact in the inertial confinement fusion experiments is most prominent. For the reasons of physical clarity we will assume that the pump wavelength is \( \lambda_0 = 1 \mu\text{m} \) and the time scale, expressed in picoseconds, will be dependent on that assumption.

The dependence of temporal evolution of the forward propagating electron plasma wave amplitude on the laser intensity is illustrated in Fig. 1(a), for plasma parameters \( T = 0.2 \text{keV} \) and \( n = 0.240n_{cr} \).

The saturated plasmon amplitude is clearly proportional to the laser intensity: its value is 0.09 for \( a = 0.02 \) and two times higher for \( a = 0.04 \), corresponding to a plain whose distance from the left plasma slab boundary is \( x = 25\lambda_0 \). This is only natural, since the electron quiver velocity, and consequently the instability growth rate, scale with the pump intensity. The oscillation frequency of the plasmon amplitude is also proportional to the laser intensity. This frequency is of the order \( 10^{-3}\omega_0 \) and obviously originates from beating with the ion fluctuations. It is also apparent that the amplitude is growing more rapidly and saturates earlier when the pump is more intense. The same conclusions can be applied to the ion-acoustic wave amplitude, whose temporal evolution for the same set of plasma parameters is depicted in Fig. 1(b). Comparison of the corresponding amplitude evolutions on Figs. 1(a) and (b) reveals that the instability saturates simultaneously with the
Figure 1. Temporal evolution of the forward-propagating electron plasma wave (a) and the ion-acoustic wave (b) amplitudes for plasma parameters $T = 0.2\,\text{keV}$, $n = 0.240n_{cr}$ and various pump amplitudes and distances from the left plasma slab boundary: (a) $a = 0.02$, $x = 25\lambda_0$ (solid line), $a = 0.02$, $x = 75\lambda_0$ (dotted line), $a = 0.04$, $x = 25\lambda_0$ (dashed line); (b) $a = 0.02$, $x = 25\lambda_0$ (solid line), $a = 0.04$, $x = 25\lambda_0$ (dashed line).

The ion-acoustic amplitude reaching its maximum value, which is less than 1% of the bulk plasma density for plasma parameters used in our simulations. Even such a small value proves to be quite sufficient to nonlinearly saturate the TPD instability, which is in quite a good agreement with the experimental evidence [15, 20].

By comparing the plasmon amplitude temporal evolution at $x = 25\lambda_0$ and $x = 75\lambda_0$ in Fig. 1(a), we conclude that the initial amplitudes of oscillations of $N_1$ are lower deeper into the plasma, and also take some more time to saturate. Nevertheless, after a time of the order of 10 ps the saturation occurs at roughly the same amplitude throughout the plasma slab. The same conclusions are valid concerning the oscillations of the ion-acoustic wave amplitude, $N_s$. We will see later that this is no longer the case when the secondary coupling, responsible for the saturation of the instability, is non-resonant.
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Figure 2. Temporal evolution of the forward-propagating electron plasma wave amplitude for $a = 0.03$, $n = 0.248n_{cr}$ and various electron temperatures and distances from the left plasma slab boundary: $T = 0.2\text{keV}$, $x = 25\lambda_0$ (dashed line), $T = 0.6\text{keV}$, $x = 25\lambda_0$ (solid line), $T = 0.6\text{keV}$, $x = 75\lambda_0$ (dotted line).

The electron temperature dependence of the plasmon amplitude temporal evolution is displayed in Fig. 2. The saturation value of the plasmon amplitude $N_1$ clearly scales with the square root of the electron temperature, and our simulations indicate that the same can be said about the ion-acoustic wave amplitude. This is caused by the fact that the group velocities of the electrostatic waves in plasma, calculated through (9), increase linearly with $\beta_e$. It can also be inferred that the electrostatic wave amplitudes saturate much earlier when the electron temperature is higher, as the higher electron thermal energy leads to a more efficient damping of the amplitude oscillations. On the other hand, deeper into the plasma the amplitudes saturate with considerable delay: for the parameters in Fig. 2 and the electron temperature of $0.6\text{keV}$, saturation occurs after about $10\text{ps}$ for $x = 75\lambda_0$, and less than $3\text{ps}$ for $x = 25\lambda_0$.

Since the electron plasma wave group velocity decreases with increasing plasma density, as inferred from (9), we should expect that its saturation amplitude exerts the same dependence. This assumption can readily be confirmed by inspection of Fig. 3, where the plasma density dependence of the plasmon amplitude temporal evolution is displayed for the parameters $a = 0.03$, $T = 0.2\text{keV}$. Even though the initial amplitude oscillations are far more rapid for lower plasma densities than for the higher ones, they reach the saturation at approximately the same time, which is of the order of $10\text{ps}$. While the plasmon saturation amplitude is about $14\%$ for $n = 0.240n_{cr}$, its value is only $1\%$ lower for $n = 0.248n_{cr}$. Such a weak density dependence, however, does not apply to the ion-acoustic wave amplitude, which plunges from $0.4\%$ to $0.06\%$ in the same interval of densities. This is understandable since the wave vector intensities decrease as the plasma density approaches $n_{cr}/4$, and the coefficient $C_3$ in (4) is particularly sensitive to this effect. Our model thus confirms that even very low values of ion fluctuations turn out to be sufficient to procure saturation of the instability, especially when plasma density is close to $n_{cr}/4$. Since the model is constructed for the optimum case of maximum instability...
Figure 3. Temporal evolution of the forward-propagating electron plasma wave amplitude for $a = 0.03$, $T = 0.2\text{keV}$, $x = 75\lambda_0$, and for plasma densities: $n = 0.240n_{cr}$ (solid line) and $n = 0.248n_{cr}$ (dotted line).

Figure 4. Spatio-temporal evolution of the forward-propagating electron plasma wave amplitude for $a = 0.03$, $T = 0.2\text{keV}$ and $n = 0.240n_{cr}$, when the secondary coupling is resonant. The plot displayed in Fig. 4 enables us to gain better insight into the spatio-temporal dynamics of TPD, by observing the evolution of the electron plasma wave amplitude for a typical set of laser and plasma parameters, in the case of resonant secondary coupling. The character of the dynamics is simply periodic throughout the plasma slab, with natural exception of the narrow bands along the boundaries. The saturation level remains mainly constant, approximately 0.14 for the chosen increment, it is capable of reproducing the concrete values of ion fluctuations that provide saturation for different sets of laser and plasma parameters.
Figure 5. Initial spatio-temporal evolution of the absolute value of the forward-propagating electron plasma wave amplitude for $a = 0.03$, $T = 0.2\text{keV}$ and $n = 0.24\n_{cr}$, when non-resonance of the secondary coupling is taken into account.

parameters, and only a slight stretching of the temporal oscillation profile towards the right boundary prevents the plot from being rather monotonous. The solid line in Fig. 3 actually represents such a profile at $x = 75\lambda_0$.

Our next task is to investigate the influence of non-resonance of the secondary coupling of the daughter electron plasma waves with an ion-acoustic wave on the spatio-temporal dynamics of the wave amplitudes, by simulating the system of equations (1)–(4) in the case $\Omega \neq 0$. Some of the features of the instability in this case can be deduced from the plot in Fig. 5, where the initial spatio-temporal evolution of the absolute value of the forward-propagating electron plasma wave amplitude is displayed for the same set of laser and plasma parameters as in Fig. 4. Even a superficial insight reveals the distinct non-uniformity of the plasmon amplitude throughout the plasma slab, which was absent in the case of perfect secondary matching. This corresponds to the benchmark experimental results of Mayer’s group [15], obtained by using CO$_2$ laser radiation with $10.6\mu\text{m}$ wavelength, where the Thomson scattering streak record of the spatial development of TPD wave intensity confirms significant spatial non-uniformity of the electron plasma wave intensity, with closely spaced local maxima of resolution limited size. The same streak record suggests that the TPD wave intensity saturates after about $50\text{ps}$, and afterwards oscillates at the frequency corresponding to that of the ion-acoustic waves. This agrees with the wave behavior that manifests itself in Fig. 5, taking into account that our time-scale is given in picoseconds for the supposed laser wavelength $\lambda_0 = 1\mu\text{m}$. Thus the plasmon amplitude saturates after about $6\text{ps}$ in the vicinity of the left plasma slab boundary, and up to $10\text{ps}$ towards the right boundary. As anticipated, the saturation generally occurs later than in the case of resonant secondary coupling, and the saturation amplitude is considerably higher, because the ion-coupling mechanism is less efficient when $\Omega \neq 0$. These features of the wave dynamics clearly become more pronounced towards the right plasma slab boundary,
as the impact of finite $\Omega$ causes a cumulative effect on larger space scales. Apparently, the impact of $\Omega$ is significant even though its value is of the order $10^{-3}$ for most parametric regimes of interest.

Some interesting conclusions can be drawn by observing the long-term spatio-temporal evolution of the absolute value of the forward-propagating electron plasma wave amplitude, displayed in Fig. 6. After the initial period of rapid oscillations, which unfolds according to the previously described scenario, the electron plasma wave amplitude saturates temporarily to a value of 0.14 to 0.17, depending on $x$, for the chosen laser and plasma parameters, and then enters a period of rapid oscillations. The regime of these oscillations is clearly quasi-periodic, with at least two characteristic frequencies, apparently generated by beating of the ion-acoustic frequency with the frequency mismatch of the secondary coupling.

These frequencies are better distinguished in Fig. 7, which provides us with an insight into the long-term temporal evolution of the absolute value of the plasmon amplitude in $x = 25\lambda_0$, for the same laser and plasma parameters as in Fig. 6. The maximum amplitude of these rapid oscillations is significantly above the saturation amplitude and can even amount to 25% closer to the right plasma slab boundary. The complexity of the wave dynamics increases simultaneously, barring the narrow band in the vicinity of the right plasma boundary in which the boundary effect prevails, although the oscillations always preserve their quasi-periodic nature. Every maximum is followed by an interval when the amplitude slowly decreases, gradually reaching the saturation value, after which another period of rapid oscillations occurs and so on. This is somewhat similar to the burst-like behavior of the instability in inhomogeneous plasmas, when the profile modification near the quarter-critical density is taken into account, as the density profile steepens and relaxes under the influence of the ponderomotive force of the pump wave [1, 2, 9]. We conclude that TPD instability should occur in bursts even in homogeneous plasmas, due to the inherently non-resonant nature of the ion saturation mechanism, although the
amplitudes of these bursts should be considerably smaller than in the above mentioned case of ponderomotive profile steepening. An increased, burst-like production of hot electrons is also to be expected during periods of instability enhancement.

4. Conclusions
A nonlinear, hydrodynamic model of two-plasmon decay in homogeneous laser irradiated plasma is utilized, in order to investigate spatio-temporal evolution of the slowly varying electron plasma wave amplitude during the course of the instability, as well as its dependence on laser and plasma parameters. Bearing in mind the fact that the instability is highly resonant, we constructed the model for the case of maximum TPD growth rate, and applied it to the homogeneous slab of deuterium plasma near the quarter-critical density. The model introduces the secondary coupling of daughter electron plasma waves with the ion-acoustic waves, which proved to be the principal saturation mechanism of the instability. The saturation takes place simultaneously with the ion-acoustic wave reaching its maximum value, which is less than one percent for typical parameter regimes.

Spatio-temporal evolution of the plasmon amplitude is inspected, as well as its scaling with pump intensity and plasma temperature and density. When the secondary coupling is taken to be resonant, the wave amplitudes saturate during the first 10 picoseconds throughout the plasma slab and their spatial profile is basically uniform. This scenario changes significantly when non-resonance of the secondary coupling is taken into account. The introduction of the finite frequency mismatch $\Omega$ contributes to greater richness and complexity of the wave dynamics and causes distinct non-uniformity of the spatial profile of the instability. It also renders the long-term dynamics of the instability burst-like, with alternating intervals of rapid amplitude oscillations and subsequent saturation, the value of the saturation amplitude being considerably higher than in the case of resonant secondary coupling.
To our knowledge, this is the first prediction of the burst-like development of TPD instability in homogeneous plasma, not caused by the ponderomotive steepening and subsequent relaxing of the plasma density profile. Accordingly, burst-like nature of the hot electron production should be one of the direct consequences of the quasi-periodic electron plasma wave amplitude dynamics.

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References
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