Parametric Coupling of Crossed Laser Beams in Plasma under Raman Backscatter Instability

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ABSTRACT

Laser-plasma coupling is an important area of research for applications such as inertial confinement fusion (ICF) and laser plasma accelerators. An important physical process that affects the efficiency of these applications is stimulated Raman scattering (SRS). In the present work the nonlinear interaction between two crossed laser beams in homogenous thermal plasma is investigated under backward stimulated Raman scattering (BSRS) conditions in the non-relativistic regime. The study predicts excitation of diagonal Langmuir (electrostatic) wave which is resonantly driven by pump and scattered (electromagnetic) waves. The evolution equations for pump, scattered and diagonal Langmuir waves excited due to the interaction are set up. The temporal evolution of amplitudes of pump, scattered and Langmuir waves for back SRS instability have been obtained and numerically solved using numerical techniques. The temporal growth rate, saturation time and saturation amplitude of waves excited by two crossed (perpendicular) lasers are studied and compared with the single beam case. The model considers pump depletion to be the dominant saturation mechanism. The study points towards a new type of instability that is absent in single beam case. The results should be useful in understanding the nonlinear propagation characteristics of multiple electromagnetic waves in ICF and self modulated laser wake field acceleration (SM-LWFA) processes.

Keywords: Stimulated Raman scattering; Crossed laser beams; Langmuir waves

1. INTRODUCTION

The most important laser plasma instabilities that significantly affect direct and indirect inertial confinement fusion (ICF) [1-3] experiments are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) [4-10]. Due to these instabilities the laser beams are scattered away from the target, thereby reducing the energy available to drive the compressive heating of the nuclear fuel. Stimulated Raman scattering (SRS) in plasma is the decay of an incident (pump) light wave into a frequency-downshifted scattered light wave and an electrostatic (Langmuir) wave. The pump, scattered and plasma wave modes parametrically couple with each other leading to SRS instability, when the waves satisfy appropriate frequency and wave number matching conditions. The scattered and plasma waves grow at the expense of the pump. The SRS process occurs at plasma densities less than the quarter critical ($n_0 \le n_{cr}/4$ i.e. $\omega_0 \ge 2\omega_p$) density. Where $\omega_0(\omega_p)$ is the laser (plasma) frequency and $n_0(n_{cr})$ is the initial (critical) plasma density[5].

Several workers have studied SRS process due to a single laser beam in detail. Since laser beams overlap in the coronal plasma surrounding the nuclear fuel, it is important to analyze SRS (and other parametric instabilities) driven by two (or more) crossed beams. The presence of multiple laser beams in plasma can lead to a new set of interesting phenomena. One of the potential applications of two colliding lasers can be the excitation of large amplitude Langmuir waves, which can in turn accelerate electrons to ultra high energies. Simulation studies [11, 12] show that large amplitude plasma waves can be excited by two crossed laser pulses, or by two copropagating electromagnetic pulses where a long trailing pulse is modulated efficiently by the periodic plasma wake behind the leading short laser pulse [13].

In this paper we present an analytical study of the nonlinear interaction between two crossed (perpendicular) laser beams propagating in completely ionized plasma, in the non-relativistic regime. Each pump wave is associated with a backscattered wave and an oblique Langmuir wave and the coupling of the waves satisfy the backward stimulated Raman scattering (BSRS) conditions. Generation of oblique Langmuir waves have been predicted in recent simulation studies [11, 12]. The Maxwell’s and Poisson’s equations are used in conjugation with the hydrodynamic equations for electrons, to derive a set of coupled equations. The analysis neglects finite pulse size effects, since the saturation time for BSRS instability (≈ 0.1ps) is much less than typical pulse durations (≈ 10.0 ps) [14]. The nonlinearities like nonlinear frequency shift[15] and Landau damping have been neglected because for plasma temperatures considered in the present study, the thermal velocity of plasma electrons will be much less than the Langmuir wave phase velocity ($k_p\lambda_D << 1$, where k_p is the Langmuir wave propagation constant and λ_D is the Debye length). Some of the possible nonlinearities responsible for BSRS saturation can be pump depletion [16], wave breaking [17] and secondary nonlinear process such as Langmuir decay instability (LDI) [15]. In the present study it is considered that pump depletion is the dominant mechanism leading to saturation of BSRS instability.

The outline of this paper is as follows. Section II gives the governing equations for SRS process. In Section III nonlinear temporal evolution of laser, scattered and Langmuir waves are set up. Section

IV deals with the numerical analysis of backward stimulated Raman instability. The main results are summarized in Section V.

2. GOVERNING EQUATIONS

The wave equation governing the propagation of two laser beams through completely ionized, homogeneous plasma is given by

$$\frac{\partial^2 \mathbf{E}(\mathbf{r},t)}{\partial t^2} + c^2\left[\nabla\times(\nabla\times\mathbf{E})\right] = -4\pi\frac{\partial \mathbf{J}(\mathbf{r},t)}{\partial t} \tag{1}$$

where $\mathbf{E}(\mathbf{r}, \mathrm{t})$ $\left[= \sum_{i=1,2}\left(\mathbf{E}_{r_i} + \mathbf{E}_{s_i}\right) + \mathbf{E}_p\right]$ is the combined electric field due to two laser beams, two scattered waves and a resultant Langmuir wave denoted by subscripts r_i, s_i, p respectively.

In the non-relativistic limit the momentum equation is given by

$$\frac{\partial \mathbf{v}}{\partial t} + \frac{1}{2}\nabla v^2 + \frac{e}{m}\mathbf{E} + \frac{\gamma_e k_B T}{mn}\nabla n = 0 \tag{2}$$

where $n\left(= n_0 + \delta n\right)$ is the plasma electron density, γ_e (=3) is the ratio of specific heats for an electron fluid and $\mathbf{v} = \sum_{i=1}^{2}\left(\mathbf{v}_{r_i} + \mathbf{v}_{s_i}\right) + \mathbf{v}_p$ is the resultant velocity of plasma electron due to all the waves. In Eq. (2) the last term on L.H.S. represents thermal contribution. It may be noted (Eq. (2)) that in the non-relativistic limit, if the electron fluid is initially vortex free then it remains so during subsequent stages of interaction ($\mathbf{v}\times(\nabla\times\mathbf{v} - e\mathbf{B}/mc) = 0$, where $\mathbf{B}$ is the magnetic field component of the laser).

In the presence of the laser beams, the density and velocity perturbations of the electrons are governed by the continuity equation

$$\frac{\partial n}{\partial t} + \nabla.(n\mathbf{v}) = 0 \quad . \tag{3}$$

Therefore Eq. (1) reduces to,

ISBN: 978-93-83083-88-6

$$\frac{\partial^2 \mathbf{E}(\mathbf{r},t)}{\partial t^2} + c^2\left[\nabla\times\{\nabla\times\mathbf{E}(\mathbf{r},t)\}\right] - c^2\nabla^2\mathbf{E}(\mathbf{r},t)$$

$$= -4\pi\left[-en\left\{-\frac{e\mathbf{E}}{m} - \frac{1}{2}\nabla\left(v^2\right) - \frac{\gamma_e k_B T}{mn}\nabla n - \mathbf{v}(\nabla.\mathbf{v})\right\} + e\mathbf{v}(\mathbf{v}.\nabla\delta n)\right] \tag{4}$$

Linear as well as nonlinear source terms are present on the right side of
Eq. 4. The first (linear) term on the right hand side of Eq. 4 is generated due to interaction of plasma electrons with the electric fields. The second and third terms represent the ponderomotive force and thermal contribution respectively. The last two terms are due to plasma electron density perturbations.

3. TEMPORAL EVOLUTION OF FIELD AMPLITUDES

The frequency and wave vector matching conditions [11, 12] imposed by SRS process are given respectively by

$$\omega_{r_i} = \omega_{s_i} + \omega_p \text{ and } \mathbf{k}_{r_i} = \mathbf{k}_{s_i} + \mathbf{k}_p \quad (\text{for } i\text{=1 and 2}). \tag{5}$$

The form of electric field of the pump, scattered and plasma waves may be represented by

$$\mathbf{E}_j(\mathbf{r},t) = \frac{\hat{\mathbf{e}}_j}{2}\left[\varepsilon_j e^{i(\mathbf{k}_j.\mathbf{r}-\omega_j t)} + \varepsilon_j^* e^{-i(\mathbf{k}_j.\mathbf{r}-\omega_j t)}\right] \tag{6}$$

and the corresponding forms of the plasma electron velocities due to individual fields are given as

$$\mathbf{v}_j(\mathbf{r},t) = \frac{e\hat{\mathbf{e}}_j}{2im\omega_j}\left[\varepsilon_j e^{i(\mathbf{k}_j.\mathbf{r}-\omega_j t)} - \varepsilon_j^* e^{-i(\mathbf{k}_j.\mathbf{r}-\omega_j t)}\right] \tag{7}$$

where $j = r_i, s_i, p$; $\hat{\mathbf{e}}_j$ are unit vectors along the electric field directions and ε_j are the field amplitudes of the pump, scattered and Langmuir waves. Considering the two pump waves to be linearly polarized and propagating along the x and z directions, the diagonal Langmuir wave is excited at an angle $\pi/4$ with respect to propagation vectors of each pump wave. Further, for BSRS process the generated scattered wave propagation vector (k_{s_i}) makes an angle π with respect to corresponding propagation vectors (k_{r_i}) of the laser beams. For such a configuration we have $\hat{\mathbf{e}}_{r_i}.\hat{\mathbf{e}}_p = \hat{\mathbf{e}}_{s_i}.\hat{\mathbf{e}}_p = 1/\sqrt{2}$ and $\hat{\mathbf{e}}_{r_i}.\hat{\mathbf{e}}_{s_i} = 1$.

ISBN: 978-93-83083-88-6

The amplitudes (ε_j) are assumed to be slowly varying in space and time. Substituting Eqs. 6 and 7 into Eq. 4 and considering that the plasma electron density perturbation obeys Poisson's equation $\{\delta n = (-\nabla.\mathbf{E}_p / 4\pi e)\}$ the coupled (pump, scattered and plasma) wave equations having contributions due to thermal and ponderomotive effects are obtained. Observing the interaction at a localized (crossing) point in space in the laboratory frame (ignoring the spatial variation of field amplitudes), the equation governing the temporal evolution of wave amplitudes, are given by

$$\frac{\partial \varepsilon_{r_i}}{\partial t} = -\frac{e\omega_{pe}^2}{4m\omega_{r_i}\omega_{s_i}\omega_p}\left[\frac{k_{r_i}}{\sqrt{2}} + k_p\left\{1 + \frac{\omega_{s_i}\omega_p}{\omega_{pe}^2}\right\}\right]\varepsilon_{s_i}\varepsilon_p, \tag{8a}$$

$$\frac{\partial \varepsilon_{s_i}}{\partial t} = \frac{e\omega_{pe}^2}{4m\omega_{r_i}\omega_{s_i}\omega_p}\left[\frac{k_{s_i}}{\sqrt{2}} - k_p\left\{1 - \frac{\omega_{r_i}\omega_p}{\omega_{pe}^2}\right\}\right]\varepsilon_{r_i}\varepsilon_p^*, \tag{8b}$$

for i=1, 2 and

$$\frac{\partial \varepsilon_p}{\partial t} = \sum_{i=1}^{2}\frac{e\omega_{pe}^2 k_p}{4m\omega_{r_i}\omega_{s_i}\omega_p}\varepsilon_{r_i}\varepsilon_{s_i}^* \tag{8c}$$

where $\omega_{r_i,s_i}^2 = \omega_{pe}^2 + c^2 k_{r_i,s_i}{}^2$, $\omega_p^2 = \omega_{pe}^2 + 3v_{th}^2 k_p^2$. The complex, slowly varying amplitudes (ε_j) can be written in terms of real amplitudes $(q_j(t))$ and real phases $(\alpha_j(t))$ as

$$\varepsilon_j = q_j(t)e^{i\alpha_j(t)} \ . \tag{9}$$

Substituting Eq. 9 into the set of Eqs. 8 and equating real and imaginary parts, the real amplitudes and phases for pump, scattered and Langmuir waves respectively are found to evolve as

$$\frac{\partial q_{r_i}}{\partial t} = L_i q_{s_i} q_p \cos\beta_j \quad , \tag{10a}$$

$$\frac{\partial q_{s_i}}{\partial t} = S_i q_{r_i} q_p \cos\beta_j \quad , \tag{10b}$$

ISBN: 978-93-83083-88-6

$$\frac{\partial q_p}{\partial t} = \sum_{i=1}^{2} P_i q_{r_i} q_{s_i} \cos\beta_j \ , \tag{10c}$$

and

$$q_{r_i} \frac{\partial \alpha_{r_i}}{\partial t} = -L_i q_{s_i} q_p \sin\beta_j \ , \tag{11a}$$

$$q_{s_i} \frac{\partial \alpha_{s_i}}{\partial t} = -S_i q_{r_i} q_p \sin\beta_j \ , \tag{11b}$$

$$q_p \frac{\partial \alpha_p}{\partial t} = -\sum_{i=1}^{2} P_i q_{r_i} q_{s_i} \sin\beta_j , \tag{11c}$$

where

$$\beta_j = \begin{cases} \beta & , \ j = r_i \\ -\beta & , \ j = s_i \\ -\beta & , \ j = p \end{cases}$$

and $\beta = \alpha_{r_i} - \alpha_{s_i} - \alpha_p$

$$L_i = -\frac{e\omega_{pe}^2}{4m\omega_{r_i}\omega_{s_i}\omega_p}\left[\frac{k_{r_i}}{\sqrt{2}} + k_p\left(1 + \frac{\omega_{s_i}\omega_p}{\omega_{pe}^2}\right)\right],$$

$$S_i = \frac{e\omega_{pe}^2}{4m\omega_{r_i}\omega_{s_i}\omega_p}\left[\frac{k_{s_i}}{\sqrt{2}} - k_p\left(1 - \frac{\omega_{r_i}\omega_p}{\omega_{pe}^2}\right)\right],$$

$$P_i = \frac{e\omega_{pe}^2 k_p}{4m\omega_{r_i}\omega_{s_i}\omega_p}.$$

The expressions for a single laser beam can be obtained by considering either q_{r_1} or q_{r_2} zero in the set of Eqs. 10 and 11.

4. NUMERICAL ANALYSIS

From the set of Eqs. 10 and 11 the nonlinear coupled temporal evolution of amplitudes and phases of the pump, scattered and Langmuir waves, due to two crossed laser beams interacting with the plasma, is obtained. The intensity and frequency of the two beams are assumed to be the same. The equations are solved numerically using fourth order Runge-Kutta method. The laser and plasma parameters are $\omega_{r_i} = 6.283\times10^{15}\,\text{rad}\,\text{sec}^{-1}$, $T_e = 3$ keV and $n_0/n_{cr} = 0.242$. The initial values for amplitudes and phases are respectively $q_{0s_i} \approx q_{0p} \approx 0.01\, q_{0r_i}$ and $\alpha_{0r_i} \approx \alpha_{0s_i} \approx \alpha_{0p} \approx 0$ (so that the amplitude of the Langmuir waves generated is maximum), where $q_{0r_i} = a_{0r_i}\omega_{r_i} mc/e$ and the laser strength parameter $a_{0ri} = 0.028$.

Temporal evolution of amplitudes of scattered and Langmuir waves due to two crossed laser beams is compared with those obtained by propagation of a single beam, in Fig. 1. The continuous curves show evolution of waves for two crossed beams (having same intensities), while dashed curves show the evolution of waves for a single beam. Numerical solutions show that the amplitudes of scattered and Langmuir waves increase and reach a maximum value (saturation amplitude) and then decay with time. However, simultaneously the amplitude of pump waves experiences similar but opposite evolution process. The saturation amplitude of Langmuir wave increases by about 41% as compared to the single beam case, while the saturation time (the time taken by wave amplitude to reach its maximum value) decreases by about 29%. It may be noted that since the electric field amplitude of the generated Langmuir wave is much less than the wave breaking limit [17, 18], wave breaking process is not responsible for saturation. Further, it has been experimentally shown that LDI sets in on a time scale (~few ps) [15] which is longer than the saturation time (~0.1 ps) as seen in Fig. 1. Hence LDI can be neglected in the present analysis. Consequently, pump depletion is the dominant mechanism for BSRS saturation in the present study. The density perturbations are compared in Fig. 2 for the two cases. In case of two beams the density perturbations driven by the resultant Langmuir wave is significantly strong as compared to the single beam interaction.

The effect of plasma temperature on the evolution of amplitudes of waves for two laser beams propagating in plasma is shown in Fig. 3. It is observed that early time saturation (fast growth) occurs at lower temperature (0.3 keV, dashed curve) as compared to higher temperature (3 keV, continuous curve). However, the saturation amplitude of Langmuir wave is independent of temperature. The initial stages of amplitude evolution correspond to the linearized regime as observed in Figs. 1 and 2. The linear growth rate for the single beam case, as predicted by earlier

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workers [4, 5] can be recovered if the coupled nonlinear equations of our model are linearized. In this regime the pump amplitude is non-evolving ($q_r = q_{0r}$), while the scattered and plasma wave amplitudes evolve exponentially ($q_{s,p} = q_{0s,0p}\exp(\Gamma t)$, where $\Gamma = q_{r0}(\sum_{i=1}^{2} S_i P_i)^{1/2}$ is the linearized temporal growth rate). Since at T_e =0.3 keV, $\sum_i S_i P_i = 1.053\times10^{13}$ whereas at T_e =3 keV, $\sum_i S_i P_i = 9.665\times10^{12}$, it may be concluded that an increase in plasma temperature leads to decrease in linearized growth rate.

5. SUMMARY AND CONCLUSIONS

In the present paper, the interaction of two crossed laser beams in underdense plasma has been investigated analytically and numerically. A set of nonlinearly coupled equations describing the temporal evolution of the amplitudes and phases of the pump, scattered and Langmuir waves is set up. Solutions of the coupled mode equations under BSRS instability due to two laser beams have been obtained and compared with the single beam case. The evolution process of the waves is characterized by three important factors, the growth rate, saturation time and saturation amplitude. For the initial conditions considered in the present study the evolution equations for the pump, scattered and Langmuir waves, describe a set of nonlinearly coupled harmonic oscillators with no damping term. Hence the nonlinear temporal evolution of the coupled amplitudes is periodic, due to absence of dissipation mechanisms in our analysis.

The study demonstrates that the amplitudes of the scattered and the resultant Langmuir waves saturate at an early time (faster growth rates) for the two laser beam case as compared to the single beam case. Therefore the interaction of two laser beams with plasma enhances the destabilization (reduction in saturation time of scattered and Langmuir waves) of the BSRS process as compared to the single beam case. This result can be of significant importance for direct drive ICF experiments, which involve a symmetric arrangement of multiple laser beams directly irradiating a tiny pellet (fuel). The interaction of two crossed laser beams with underdense plasma can occur in the coronal region of the plasma fuel. The study shows that for the present parameters (which are close to experiments on ICF [19]), BSRS instability will be significantly destabilized due to crossing of two laser beams in the coronal plasma.

Further, the study of effects of plasma temperature on the nonlinear coupled temporal evolution of waves, due to two crossed laser beams indicates that if the plasma temperature reduces, the diagonal Langmuir and the scattered waves undergo early time saturation. Thus the increase in temperature tends to enhance the BSRS process. However, the saturation amplitude of the Langmuir wave is independent of temperature. Therefore, interaction of two crossed laser beams with hot coronal plasma (in ICF experiments) will be more unstable (large saturation time) to BSRS instability as compared to the low temperature corona.

It is shown that, the interaction of two crossed laser beams with plasma leads to enhancement of the saturation amplitude (sharp density perturbations) of the diagonal Langmuir wave. Therefore the present study provides us with a novel method of amplification of Langmuir wave amplitude using two low intensity laser beams, which can find application in self-modulated laser wake field acceleration (SM-LWFA) [20, 21]. The large amplitude Langmuir wave generated due to two crossed laser beams will enhance the trapping and acceleration of background plasma electrons, by the subsequent side and forward SRS processes as compared to single beam SM-LWFA scheme[17]. The results of the present analysis are consistent with recently reported simulation studies [11, 12].

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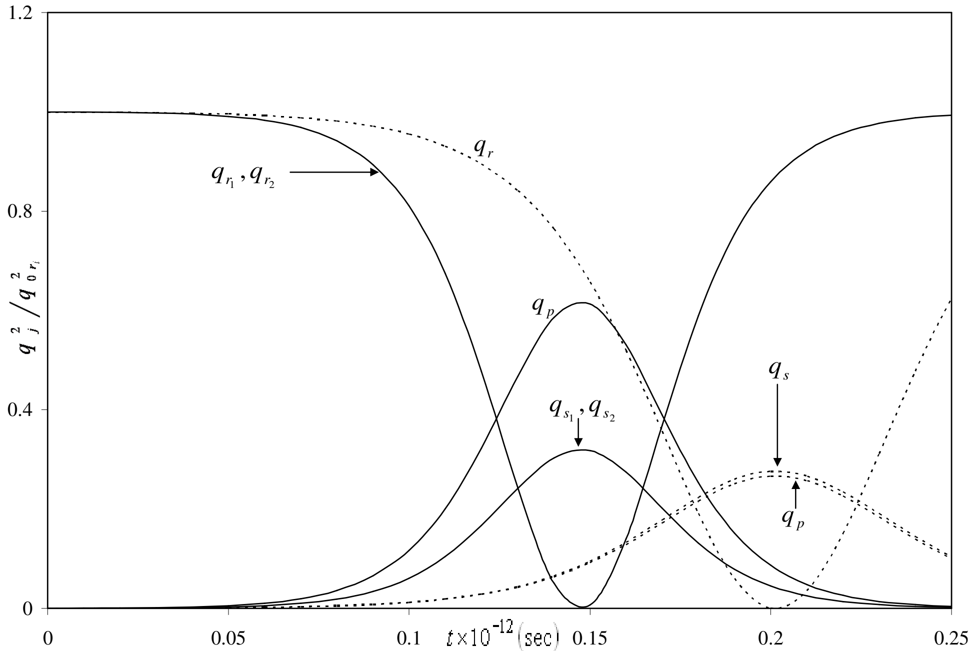
FIGURE CAPTIONS

Fig. 1. Nonlinear temporal evolution of amplitudes q_j ***with time for BSRS instability due to two crossed beams (solid curve) of same intensity and single beam (dashed curve) also of same intensity, for*** $a_{0r_i} = 0.028$, $I_{0r_i} = 1.19\times10^{16}\, W/cm^2$ $\omega_{r_i} = 6.283\times10^{15}\,\mathrm{rad\,sec}^{-1}$, $\omega_{pe} \approx \omega_{r_i}/2$, T_e ***= 3.0 keV and*** $k_p\lambda_D \approx 5.48\times10^{-2}$.

Fig. 2. Normalized plasma density perturbation $\delta n / n_0$ ***driven by two crossed beams (solid curve) of same intensity and for single beam (dashed curve) also of same intensity, for*** $a_{0ri} = 0.028$, $I_{0r_i} = 1.19\times10^{16}\, W/cm^2$, $\omega_{r_i} = 6.283\times10^{15}\,\mathrm{rad\,sec}^{-1}$, $\omega_{pe} \approx \omega_{r_i}/2$ ***and plasma temperature*** T_e ***= 3.0 keV and*** $k_p\lambda_D \approx 5.48\times10^{-2}$.

Fig. 3. Nonlinear temporal evolution of amplitudes q_j ***with time due to two crossed beams with*** $a_{0ri} = 0.028$, $I_{0r_i} = 1.19\times10^{16}\, W/cm^2$, $\omega_{r_i} = 6.283\times10^{15}\,\mathrm{rad\,sec}^{-1}$ ***and*** $\omega_{pe} \approx \omega_{r_i}/2$ ***at plasma temperatures 3.0 keV (solid curve) and 0.3keV (dashed curve) for*** $k_p\lambda_D \approx 5.48\times10^{-2}$ ***and 1.89*** $\times10^{-2}$ ***respectively.***

ISBN: 978-93-83083-88-6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0.8
0.4
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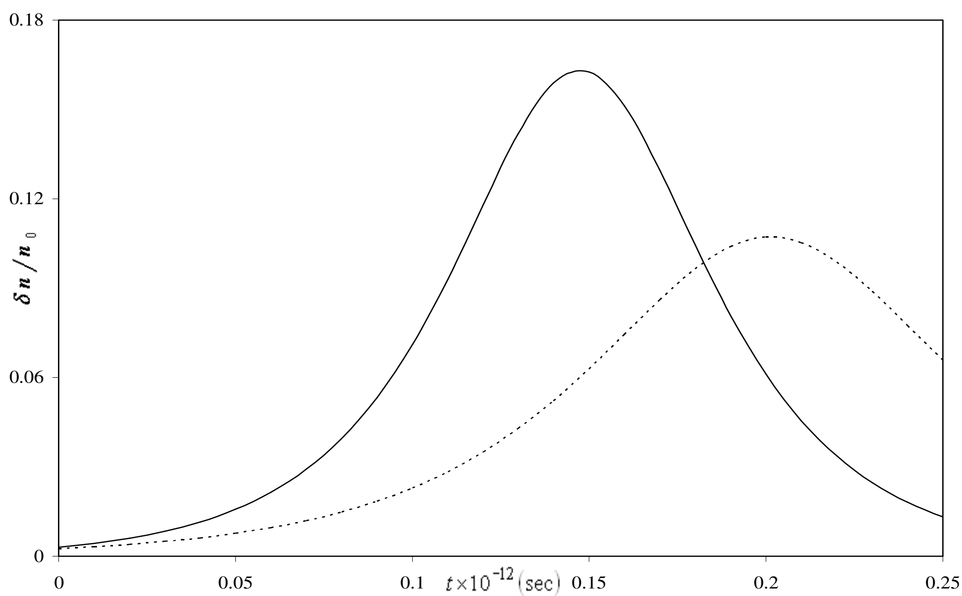
0.05
0.1
0.15
0.2
0.25
$t\times10^{-12}$ (sec)
$q_j^2/q_{0r_1}^2$
q_r
q_{r_1}, q_{r_2}
q_p
q_{s_1}, q_{s_2}
q_s
q_p

Fig. 1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0.12
0.06
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0.2
0.25
$t\times10^{-12}$ (sec)
$\delta n/n_0$

Fig. 2

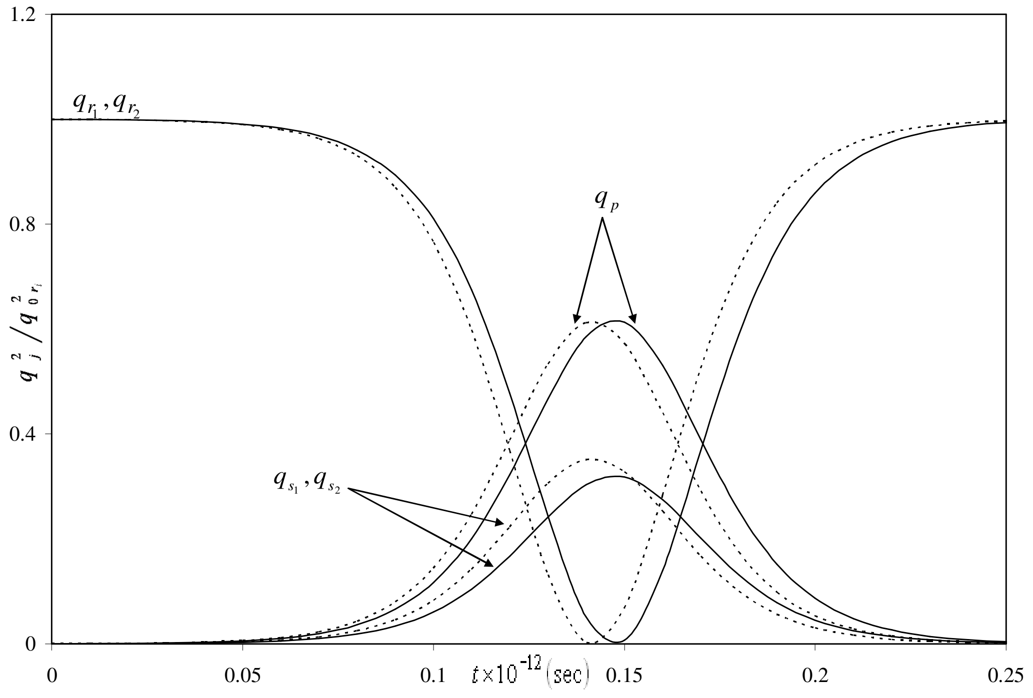

Fig. 3

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