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Stimulated Raman scattering instability in partially ionized laser-plasma*

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In a partially ionized plasma the presence of bound electrons can significantly alter the laser plasma parametric instabilities. In this paper the nonlinear dispersion relation in intense laser partially ionized plasma is analysed. The growth rate of the forward stimulated Raman scattering is significantly enhanced by the presence of bound electrons; on the other hand the backward stimulated Raman scattering is unaffected.

Keywords: intense laser partially ionized plasma, growth rate, forward stimulated Raman scattering
PACC: 5240, 4230, 5265, 5235

1. Introduction

In general, a fully ionized plasma is supposed in laser plasma interaction. In many experiments the ions are not fully ionized and hence in the laser propagation the plasma medium consists of both free and bound electrons. We find that bound electrons can result in an atomic filamentation instability (AFI)[1−5] and affect the stimulated Raman scattering (SRS), especially the forward stimulated Raman scattering (FSRS). Because in the wave equation for a laser propagating in a partially ionized plasma the polarization field associated with the bound electrons is increased, SRS instability can lead to undesirable effects, including significant amounts of light reflecting from the plasma or shining directly onto the capsule, spoiling the illumination symmetry. Also, the damping of high-phase-velocity Langmuir waves can produce superhot electrons capable of preheating the fusion fuel and reducing its compressibility. In Section 2 the nonlinear dispersion relation in an intense laser partially ionized plasma is analysed. In Section 3 the growth rate of the FSRS is calculated; the results shows that the growth rate of the FSRS is significantly enhanced by the presence of bound electrons; on the other hand the backward stimulated Raman scattering (BSRS) is unaffected.

2. Nonlinear dispersion relation in an intense laser partially ionized plasma

The wave equation in terms of the normalized vector potential a is[5]

$$\begin{aligned}&(\nabla^2 - c^{-2}\eta_0^2 - k_{\rm p}^2)a\\ =&k_{\rm p}^2 a\delta n_{\rm p}/n_{\rm p} - k_{\rm p}^2((a\cdot a)a\\ &- R\omega_0^{-4}((\partial a/\partial t\cdot\partial a/\partial t)\partial a/\partial t)),\end{aligned}\tag{1}$$

where

$$a = (a_{\rm p} + a_+ + a_-)\boldsymbol{e}_x,\tag{2}$$

$$a_{\rm p} = a_0\exp(\mathrm{i}(k_0 z - \omega_0 t) + \mathrm{c.c},\tag{3}$$

$$\begin{aligned}a_\pm = a_\pm\exp(\mathrm{i}(&(k_0 \pm k)z \pm k_\perp y\\ &- (\omega_0 \pm \omega(\omega^*))t) + \mathrm{c.c},\end{aligned}\tag{4}$$

where k_0 and ω_0 are the laser wavenumber and frequency, respectively; a_0 is the amplitude of the pump wave, $a_\pm$ are the anti-Stokes and Stokes sidebands respectively, and * denotes the complex conjugate; $k_{\rm p} = \omega_{\rm p}/c$, $\omega_{\rm p} = \left(\dfrac{4\pi e^2 n_{\rm p}}{m}\right)^{1/2}$, is the plasma frequency, $n_{\rm p}$ is the ambient plasma density in cm^{-3}, $\delta n_{\rm p}$

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is the perturbed plasma density, R is effective value in a partially ionized plasma,

$$R = P_{\rm p}/P_{\rm a} = 1.22 \times 10^{40}\eta_0\eta_2/(\lambda_0^4 n_{\rm p}); \quad (5)$$

$$P_{\rm p} = 2c(e/r_{\rm e})^2(\omega_0/\omega_{\rm p})^2 \quad (6)$$

is the critical power for relativistic focusing for linearly polarized light with a Gaussian transverse profile in a plasma, where

$$r_{\rm e} = e^2/mc^2 = 2.82 \times 10^{-13}{\rm cm} \quad (7)$$

is the classical electron radius.

$$P_{\rm a} = \lambda_0^2/(2\pi\eta_0\eta_2) \quad (8)$$

is the critical power for nonlinear focusing in a gas, $\eta_0=\Upsilon$ is the linear refractive index, η_2 is the nonlinear refractive index associated with the bound electrons in $\rm cm^2\cdot W^{-1}$, and λ_0 is the laser wavelength in μm.

The plasma current density, correct to third order in a is[6]

$$J_{\rm p} = en_{\rm p}c(1 + \delta n_{\rm p}/n_{\rm p} - a\cdot a/2)a. \quad (9)$$

The perturbed plasma density is given by[5]

$$(\partial^2/\partial t^2 + \omega_{\rm p}^2)\delta n_{\rm p}/n_{\rm p} = c^2\nabla^2(a\cdot a)/2, \quad (10)$$

where $\nabla^2 = \partial^2/\partial y^2 + \partial^2/\partial z^2$.

The nonlinear dispersion relation for a linearly polarized pump wave in a partially ionized plasma is

$$\eta_0^2\omega_0^2/c^2 - k_0^2 - k_{\rm p}^2 + k_{\rm p}^2(\alpha_0 a_0^2 + 3Ra_0^2/8) = 0, \quad (11)$$

where $\alpha_0 = 3/8 - c^2k_0^2/(8(\omega_0^2 - \omega_{\rm p}^2/4))$.

To analyse SRS, Eqs.(1) and (7) are solved, and thus we can obtain

$$\begin{aligned}&(D_+ - \Omega_0^2(c^2(k^2+k_\perp^2)/D\\ &-1-3R(2(\omega_0+\omega)^2-\omega_0^2)/2\omega_0^2))\\ &\times(D_- - \Omega_0^2(c^2(k^2+k_\perp^2)/D\\ &-1-3R(2(\omega_0-\omega)^2-\omega_0^2)/2\omega_0^2))\\ &=\Omega_0^4(c^2(k^2+k_\perp^2)/D-1-3R(2(\omega_0^2\omega^2)/2\omega_0^2)^2, \quad (12)\end{aligned}$$

where $D_\pm = \eta_0^2\omega^2 - c(k^2+k_\perp^2) \pm 2(\eta_0^2\omega_0\omega - c^2k_0k)$, $\Omega_0^2 = \omega_{\rm p}^2a_0^2/4$ and $D = \omega^2 - \omega_{\rm p}^2$. In the limit $R \to 0$, Eq.(9) reduces to previous results.[7,8]

3. Growth rate of the FSRS

By taking $k_\perp$=0, the growth rate of the FSRS can be obtained. For $Ra_0^2 \ll (4/3)\omega_{\rm p}^2/\omega_0^2$, the FSRS growth rate peaks at $k = \omega_{\rm p}/c$. It is given by the conventional expression[4,5,9−12]

$$\Gamma = \omega_{\rm p}^2 a_0/2^{3/2}\omega_0. \quad (13)$$

As Ra_0^2 increases and approaches $(4/3)\omega_{\rm p}^2/\omega_0^2$, the FSRS growth rate is

$$\Gamma = (ck\omega_{\rm p}^2/2\omega_0^2)[(1+3R/2)a_0^2/2 - (ck/\omega_0)^2]^{1/2}. \quad (14)$$

For $Ra_0^2 \gg (4/3)\omega_{\rm p}^2/\omega_0^2$, the FSRS growth rate is

$$\begin{aligned}\Gamma =&(ck\omega_{\rm p}^2/2\omega_0^2)[(1+3R/2)a_0^2/2\\ &-(ck/\omega_0)^2]^{1/2}/[3\sqrt{2}/8)Ra_0]. \quad (15)\end{aligned}$$

Figures 1 and 2 show the FSRS growth rate $(\Gamma/\omega_{\rm p})$, as a function of laser intensity $(I/10^{15}{\rm W\cdot cm^{-2}})$, where $ck/\omega_{\rm p}$=1, $n = 0.01n_{\rm c}$. The laser wavelengths in Figs.1 and 2 are $\lambda_0 = 0.35\mu$m (R=0, 3011) and 0.53 (R=0, 527), respectively. For typical gases at STP, we find that R=3011 for 0.35μm and R=527 for 0.53μm. The R=0 curves correspond to the conventional results for a fully ionized plasma, these FSRS growth rates increase as the laser intensity increases. For $R \gg 1$, the growth rates of the FSRS instability are significantly enhanced for λ_0=0.35μm, $I = 5\times10^{14} - 3\times10^{15}{\rm W\cdot cm^{-2}}$ and λ_0=0.53μm, $I = 10^{15} - 3\times10^{15}{\rm W\cdot cm^{-2}}$.

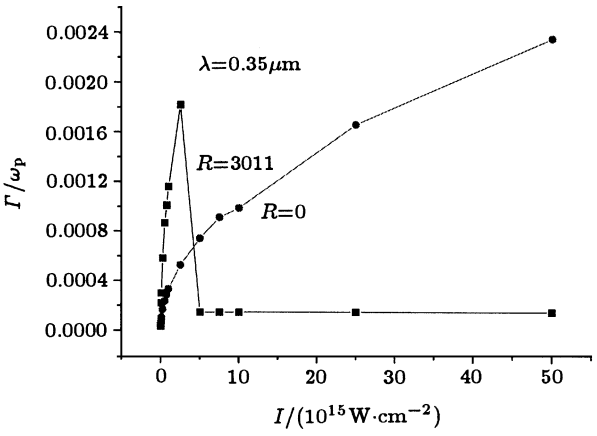


Fig.1. FSRS growth rate $(\Gamma/\omega_{\rm p})$ as a function of laser intensity $(I/10^{15}{\rm W\cdot cm^{-2}})$, for R=0 and R=3011, where λ_0=0.35μm, $n = 0.01n_{\rm c}$.

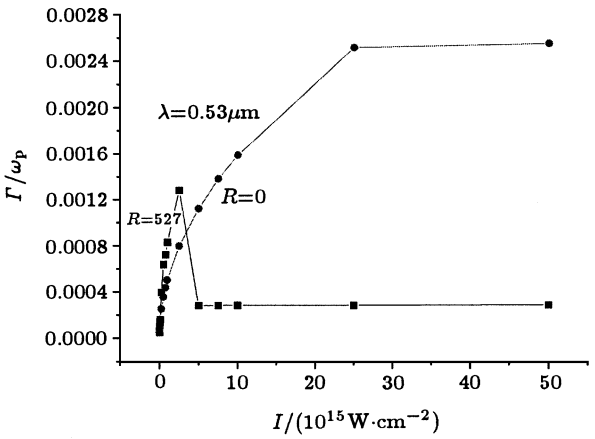


Fig.2. FSRS growth rate $(\Gamma/\omega_{\rm p})$ as a function of laser intensity $(I/10^{15}{\rm W\cdot cm^{-2}})$, for R=0 and R=527, where λ_0=0.53μm, $n = 0.01n_{\rm c}$.

For intense laser partially ionized plasma, the maximum growth rate, $\Gamma/\omega_{\rm p} = 1.82 \times 10^{-3}$, for 0.35μm light is greater than $\Gamma/\omega_{\rm p} = 1.28 \times 10^{-3}$ for 0.53μm light. Note that the laser intensities of the FSRS peak are just the options for ICF target design. For $I > 10^{15}{\rm W/cm}^2$, the growth rate of the FSRS in an intense laser partially ionized plasma decreases and tends towards zero; it is much less than that of a full ionized plasma. On the other hand, the results show the BSRS is unaffected.

4. Conclusion

The analysis and estimate on the nonlinear dispersion relation in an intense laser partially ionized plasma shows that FSRS instability develops which can have a growth rate substantially higher than the conventional FSRS: particularly a high-Z plasma at the Hohlraum wall and an indirect-drive ICF laser intensity. The results in Figs.1 and 2 are shown for 0.35μm (or Nd3ω) light and 0.53μm (or Nd2ω) light options, the maximum growth rate, $\Gamma/\omega_{\rm p} = 1.28 \times 10^{-3}$ for 0.35μm light, is greater than $\Gamma/\omega_{\rm p} = 1.82 \times 10^{-3}$ for 0.53μm light; on the other hand the BSRS is unaffected. These results indicate that the frequency-doubled 0.53μm light option is better than the frequency-tripled 0.35μm light. Particularly, due to the higher optical damage thresholds for 0.53μm laser light and higher fractional conversion into 2ω light, the laser energy on target could be increased significantly (perhaps by a factor of two). Furthermore, significantly greater bandwidth can be achieved with 2ω operation, allowing for enhanced laser beam smoothing.[1−3] So the frequency-doubled (0.53μm) laser light option could significantly enhance Shenguang-II and III capabilities. This is a very attractive option. Note that further and better understanding is needed for laser beam smoothing and laser plasma parametric instabilities.

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