Growth rate of modulation instability of a laser pulse propagating in clustered gas

ROHIT K. MISHRA AND PALLAVI JHA
Department of Physics, University of Lucknow, Lucknow, India

Abstract

This paper deals with the analysis of growth rate of modulation instability of a laser pulse propagating in a clustered gas. Finite pulse effects are considered to be a perturbation. Growth rates of modulation instability for 100 fs and 80 fs at the centroid as well as at the front and back of the pulses are evaluated and graphically analyzed. It has been shown that with decrease in pulse duration the growth rate of modulation instability increases at the front, back as well as at the centroid of the pulse. It is also shown that the change in growth rate of modulation instability at the front as well as at the back of the pulse in comparison to the centroid of the pulse for 80 fs pulse is less in comparison to that of 100 fs pulse.

Keywords: Clustered gas; Modulation instability; Columbic expansion; Growth rate

1. INTRODUCTION

Clusters are formed from high pressure gas jets resulting from the cooling associated with the adiabatic expansion of gas into vacuum (Hagena *et al.*, 1972; Taguchi *et al.*, 2010). The atoms in a cluster are held together by Van der Waals forces and these forces cannot be overcome by thermal energy. Laser cluster interaction has several applications, for example, as a source of radiation such as extreme ultraviolet and X-rays that is applicable to lithography (Kubiac *et al.*, 1996) or X-ray microscopy (Kirz *et al.*, 1995), and as a source of energetic electrons or ions (Shao *et al.*, 1996; Kumarappan *et al.*, 2001; Ditmire *et al.*, 1999; 1996). Recent theory (Mishra & Jha, 2011*b*), experiments (Alexeev *et al.*, 2003; Borisov *et al.*, 1996), and simulations (Gupta *et al.*, 2004) have shown self-focusing of intense laser radiation interacting with clustered gas. When an intense laser pulse interacts with a cluster it immediately converts the cluster into a plasma ball. Inside the cluster the total field (laser plus space charge) leads to inner ionization. Also some electrons leave the cluster (outer shell ionization) leading to a net positive charge on the cluster. The charge accumulated on the cluster is localized on the surface of the cluster and a neutral core remains inside. The dynamics of the expanding clusters gives rise to several nonlinear effects such as harmonic generation (Donnelly *et al.*, 1996) and generation of ultra-short

pulses of mono-energetic neutrons from nuclear fusion in cluster-plasmas (Ditmire *et al.*, 1999).

In many nonlinear systems, an instability leading to modulation of the steady state is exhibited as a result of interaction between nonlinear and dispersive effects. This phenomenon is referred to as modulation instability (Agrawal, 2006). Modulation instability has been studied quite extensively in many areas of science and engineering. In optics, the interest in modulation instability stems from its possible applications and relevance in ultrafast pulse generation (Sudo *et al.*, 1989), supercontinuum generation (Raja *et al.*, 2010), four-wave mixing (Boggio *et al.*, 2001), Bragg gratings (Sterke, 1998), quadratic media (Sarma & Kumar, 2012), optical fiber (Agrawal, 2006; Sarma, 2010), and parametric oscillators (Philips & Fezer, 2010). Modulation instability has also been studied in the field of meta-materials (Sarma & Saha, 2011). Development of the chirped pulse amplification technique (Strickland & Mourou, 1985) has led to the development of very high power (terawatt and petawatt) laser systems. The generation of such high power and high intensity laser pulses has caused considerable interest in the field of laser plasma interaction, which can give rise to a number of instabilities such as Raman and modulation instabilities (Antonsen *et al.*, 1993; Guerin *et al.*, 1998; Esarey *et al.*, 1996; Mori *et al.*, 1997; Sprangle *et al.*, 1997; Borghesi *et al.*, 2002; Clark *et al.*, 2005; Jha *et al.*, 2005; Kline *et al.*, 2009; Esarey *et al.*, 2009; Gill *et al.*, 2010; Zhang *et al.*, 2011). When a laser beam propagates through plasma, the ponderomotive force gives rise to low frequency

---

Address correspondence and reprint requests to: Rohit K. Mishra, Department of Physics, University of Lucknow, Lucknow 226007, India. E-mail: mrohitk@gmail.com

perturbations of the number density, which interact with the high frequency electromagnetic wave so that the amplitude of the pump wave gets modulated and the modulation instability of the electromagnetic wave occurs. Growth of modulation instability has been reported (Max *et al.*, 1974; McKinstrie *et al.*, 1992). Recently, the effect of laser pulse profile on laser plasma interaction process has been reported (Jha *et al.*, 2009; Mishra & Jha, 2011*a*). Distortion of the laser pulse profile and effect on the growth of modulation instability is shown. Liu *et al.* (2011) have investigated the modulation instability of an intense elliptically polarized laser beam propagating in un-magnetized plasma.

This paper deals with the analytical study of the effect of cluster expansion on the growth rate of modulation instability of a laser pulse propagating in tenuous clustered gas. Since Coulombic (hydrodynamic) pressure predominantly contributes to the overall expansion dynamics of small (large) clusters when strong laser fields interact with them (Ditmire *et al.*, 1996), the role of Coulombic pressure in the expansion of a single nanometer sized cluster in response to a short (≈ 100 fs and 80 fs) laser pulses has been considered in the present paper. In Section 2, the wave equation, including cluster radius expansion, group velocity dispersion, and finite pulse length effects has been set up. Considering finite pulse length effects to be a higher order effect, the lowest order solution for the wave amplitude is obtained. Section 3 deals with the evolution of the growth rate of modulation instability at the front, back, and at the centroid of the laser pulse. Summary and conclusions are presented in Section 4.

2. WAVE EQUATION

Consider a linearly polarized laser beam propagating along the z-direction in a tenuous clustered gas. The electric vector of the laser field is given by

$$\vec{E}(r, z, t) = \frac{1}{2}E_0(r, z, t)\exp[i(k_0 z - \omega_0 t)]\hat{x} + c.c., \quad (1)$$

where $E_0 (r,z,t)$ is the amplitude of the radiation field and $k_0 (\omega_0)$ is its wave number (angular frequency). Considering the individual cluster to behave like a dielectric sphere, the wave equation governing the propagation of a laser beam in clustered gas is given by

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{a}_L = \frac{4\pi e}{m_e c^3 \omega_0}\frac{\partial^2 \vec{P}}{\partial t^2}, \quad (2)$$

where $\vec{a}_L(= e\vec{E}(r, z, t)/m_e c\omega_0)$ is the normalized electric vector of the laser field. The polarization field $(\vec{P})$ arising due to the presence of the clusters may be written as

$$\vec{P} = \frac{m_e c\omega_0 n_c}{e}\left(\frac{\omega_{Mie}^2}{\omega_{Mie}^2 - \omega_0^2}\right)R_C^3\vec{a}_L, \quad (3)$$

where n_c is the cluster density and $\omega_{Mie}(= \omega_p/\sqrt{3}$, ω_p being the plasma frequency) is known as Mie frequency. The cluster radius (R_C) is a function of time t. The expansion of the cluster radius occurs on the time scale of ion motion (τ_i). Hence the change in cluster radius averaged over ion time scale is given (Mishra & Jha, 2011*b*)

$$(\Delta R_C)_{avg} = \frac{m_e^2 c^2 \omega_0^6 \tau_i^2 |a_0|^2}{\pi e^2 M_i n_{i0} R_{C0}(\omega_{Mie}^2 - \omega_0^2)^2}. \quad (4)$$

R_{C0}, M_i, n_{i0}, and a_0 ($eE_0/m_e c\omega_0$) are initial cluster radius, ion mass, initial ion density, and normalized laser amplitude, respectively. Substituting the value of polarization vector $\vec{P}$ from Eq. (3) in Eq. (2) gives

$$\left(\nabla_\perp^2 + \frac{\partial^2}{\partial z^2} + 2ik_0 z\frac{\partial}{\partial z} - k_0^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{2i\omega_0}{c^2}\frac{\partial}{\partial t} + \frac{\omega_0^2}{c^2}\right)a_0(r, z, t)$$
$$= -\frac{4\pi n_e \omega_0^2}{c^2}\left(\frac{\omega_{Mie}^2}{\omega_{Mie}^2 - \omega_0^2}\right)R_C^3 a_0(r, z, t). \quad (5)$$

With the help of the linear dispersion relation

$$-k_0^2 + \frac{\omega_0^2}{c^2} = -\frac{4\pi n_c \omega_0^2}{c^2}\left(\frac{\omega_{Mie}^2}{\omega_{Mie}^2 - \omega_0^2}\right)R_{C0}^3, \quad (6)$$

and the transformation $\tau = t - z/v_g$ (v_g is the group velocity) and $\eta = z$, the wave Eq. (5) may be written as

$$\left[\nabla_\perp^2 + \frac{\partial^2}{\partial\eta^2} - \frac{2}{v_g}\frac{\partial^2}{\partial\eta\partial\tau} - \beta\frac{\partial^2}{\partial\tau^2} + 2ik_0\frac{\partial}{\partial\eta}\right]a_0(r, \eta, \tau)$$
$$= -B|a_0|^2 a_0(r, \eta, \tau), \quad (7)$$

where $B = 12n_c m_e^2 R_{C0}\omega_0^8\omega_{Mie}^2\tau_i^2/M_i n_{i0}e^2(\omega_{Mie}^2 - \omega_0^2)^3$ and $\beta (=1/c^2 - 1/v_g^2)$ is the group velocity dispersion parameter.

Assuming slowly varying amplitude, the higher order diffraction term ($\partial^2/\partial\eta^2 \sim 1/Z_R^2$) can be neglected in comparison to $2k_0\partial/\partial\eta$. The third and the fourth terms on the left side of Eq. (7) representing finite pulse length effects are about two orders of magnitude less than $2k_0 (\partial/\partial\eta)$ and will therefore perturb the pulse amplitude. Also the propagation of a broad laser beam can be described with the help of a one-dimensional model. Therefore, the lowest order of Eq. (7) may be written as

$$\left[i\frac{\partial}{\partial\eta} - \frac{\beta}{2k_0}\frac{\partial^2}{\partial\tau^2} - \frac{1}{k_0 v_g}\frac{\partial^2}{\partial\eta\partial\tau} + \frac{B|a_0|^2}{2k_0}\right]a_0(\eta, \tau) = 0. \quad (8)$$

Considering a Gaussian laser pulse profile, the field amplitude is represented by

$$a_0(\eta, \tau) = b(\eta, \tau)\exp\left(-\frac{\tau^2}{\tau_0^2}\right), \quad (9)$$

where $b(\eta, \tau)$ is the pulse amplitude and τ_0 is the initial pulse duration. Substituting Eq. (9) into Eq. (8) and considering the variation in the pulse amplitude with respect to τ to be a higher order effect the lowest order evolution equation for the unperturbed pulse amplitude b_0 is given by

$$\left[\frac{2}{k_0 v_g \tau_0}\frac{\tau}{\tau_0} + i\right]\frac{\partial b_0}{\partial \eta} = -b_0\left[\frac{\beta}{k_0\tau_0^2}\left\{1 - 2\frac{\tau^2}{\tau_0^2}\right\}\right.$$
$$\left. + \frac{B|b_0|^2}{2k_0}\exp\left(-2\frac{\tau^2}{\tau_0^2}\right)\right]. \quad (10)$$

Solving Eq. (10) the lowest order, unperturbed amplitude is given by

$$b_0(\eta, \tau) = a_{00}\exp[A(\tau) + i\Phi(\tau)], \quad (11)$$

where a_{00} (laser strength parameter) is the initial ($\eta = 0$) amplitude of the laser pulse, $A(\tau)$ and $\Phi(\tau)$ are given by

$$A(\tau) = -\frac{\dfrac{2}{k_0 v_g \tau_0}\dfrac{\tau}{\tau_0}\left[\dfrac{Ba_{00}^2}{2k_0}\exp\left(-\dfrac{2\tau^2}{\tau_0^2}\right) + \dfrac{\beta}{k_0\tau_0^2}\left(1 - \dfrac{2\tau^2}{\tau_0^2}\right)\right]}{1 + \left(\dfrac{2}{k_0 v_g \tau_0}\dfrac{\tau}{\tau_0}\right)^2},$$

and

$$\Phi(\tau) = \frac{\dfrac{Ba_{00}^2}{2k_0}\exp\left(-\dfrac{2\tau^2}{\tau_0^2}\right) + \dfrac{\beta}{k_0\tau_0^2}\left(1 - \dfrac{2\tau^2}{\tau_0^2}\right)}{1 + \left(\dfrac{2}{k_0 v_g \tau_0}\dfrac{\tau}{\tau_0}\right)^2},$$

respectively. $A(\tau)$ leads to an exponential amplitude variation in the pulse frame while $\Phi(\tau)$ is the self-induced phase shift (self-phase modulation) experienced by a laser pulse propagating in clustered gas. $A(\tau)$ is positive (negative) at the front (back) of the pulse, hence the amplitude of the laser pulse increases at the front while it decreases at the back of the pulse, while the self-induced phase shift $\Phi(\tau)$ remains same at the front as well as back of the pulse. It may also be noted that variation in amplitude due to change in pulse length is such that for shorter pulse durations $A(\tau)$ is larger and vice-versa while the self-induced phase shift decreases with decrease in the pulse duration.

3. MODULATION INSTABILITY

Modulation instabilities are caused by the interplay between group velocity dispersion (GVD) and self-phase modulation (Sprangle *et al.*, 2000). Hence, the modulated amplitude of the laser pulse, due to GVD and finite pulse effects, may be written as the superposition of perturbed and unperturbed amplitudes, as

$$a(\eta, \tau) = \left[a_{00}\exp\{A(\tau)\} + a_{01}(\eta, \tau)\right]\exp\left(-\frac{2\tau^2}{\tau_0^2}\right)\exp\{i\Phi(\tau)\eta\}, \quad (12)$$

where $a_{01}(\eta, \tau)$ is the complex perturbed beam amplitude. Substituting Eq. (12) into Eq. (8), considering $|a_{01}| \ll |a_{00}|$, neglecting further variations in the pulse shape and considering the perturbed wave amplitude to be a sinusoidally varying function of η and τ, that is, $a_{01} = \exp\{i(K\eta - \Omega\tau)\} + \exp\{-i(K\eta - \Omega\tau)\}$ (K and Ω are the wave number and frequency of the perturbed wave amplitude, respectively), the dispersion relation for the one-dimensional modulation instability is given by

$$(1 - \hat{\Omega}^2)\hat{K}^2 + \left(\hat{\alpha} + \hat{\Phi} + 8\hat{\beta}\hat{\Omega}^2\right)\hat{K} + \left\{\hat{\Phi} - (\hat{\alpha} - \hat{\Phi})\right.$$
$$\left. - 16\hat{\beta}^2\hat{\Omega}^2\right\}\hat{\Omega}^2 = 0, \quad (13)$$

where $\hat{K} = KZ_R$ (Z_R being the Rayleigh length), $\hat{\beta} = k_0 v_g^2 Z_R\beta/8$, $\hat{\Phi} = \Phi Z_R$, $\hat{\Omega} = \Omega/k_0 v_g$, and $\hat{\alpha} = \alpha Z_R (\alpha = (Ba_{00}^2/2k_0)\exp\{2A(\tau)\eta\}\exp(-2\tau^2/\tau_0^2)$ are dimensionless quantities. The imaginary part of $\hat{K}$, in Eq. (13), gives the growth rate of modulation instability as

$$\Gamma = \frac{\hat{\Omega}}{2(1 - \hat{\Omega}^2)}\sqrt{\begin{array}{c}\left\{(\hat{\alpha} - \hat{\Phi})^2 + 2(2\hat{\Phi} + 8\hat{\beta})(\hat{\alpha} - \hat{\Phi})\right\} \\ + (2\hat{\Phi} + 8\hat{\beta})^2\hat{\Omega}^2\end{array}}. \quad (14)$$

Variation in the growth rate of modulation instability (Γ) with respect to the normalized perturbed frequency ($\hat{\Omega}$) is shown in the Figure 1. Figure 1 shows the growth rates of modulation instabilities at $\eta = 0$ as well as at the front ($\tau/\tau_0 = -0.14$) and back ($\tau/\tau_0 = +0.14$) of the pulse for 100 fs and 80 fs pulses with $\tau_0 = 100\,fs$, $\omega_0 = 2.36 \times 10^{15}s^{-1}$, $\lambda_0 = 800\,nm$, $r_0 = 40\,\mu m$, $a_{00}^2 = 6.84 \times 10^{-2}$ (peak intensity $= 1.46 \times 10^{17}$ W/cm²), $n_c = 8.0 \times 10^{13}\,cm^{-3}$, $n_0 = 1.8 \times 10^{22}\,cm^{-3}$, $R_{C0} = 30\,nm$ and $M_i = 1.39 \times 10^{-12}\,gm$. Curves a (d), b (e), and c (f) show the growth rate of modulation instability at the centroid ($\eta = 0$), at the front and back of the pulse, respectively, for 100 fs (80 fs) pulse. For both the pulses, it is seen that exponential amplitude variation ($A(\tau)$) is positive (negative) at the front (back) of the pulse that leads to increase in growth rate of modulation instability at the front and decrease at the back of the pulse.

It is seen that as the pulse duration decreases the growth rate of modulation instability increases due to increase in the exponential amplitude variation ($A(\tau)$) and decrease in the self-induced phase shift ($\Phi(\tau)$). Average enhancement in the growth rate of modulation instability of the shorter pulse is 73.17%. For 80 fs (100 fs) pulse growth rate of modulation instability increases by 3.30% (4.67%) at the front and decreases by 2.93% (4.63%) at the back of the
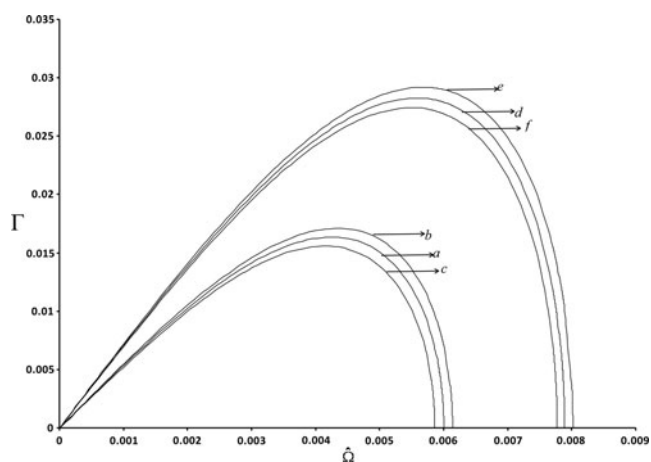
Fig. 1. Variation in the growth rate of modulation instability (Γ) with $\hat{\Omega}$ after the pulse has traversed a distance of a Rayleigh length (Z_R) at the centroid of the pulse ($\eta = 0$) (Curve a (d)), at the front ($\tau/\tau_0 = -0.14$) of the 100 fs (Curve b) and 80 fs (Curve e) pulses. Curves 'c' and 'f' represent growth rate of modulation instability at the back ($\tau/\tau_0 = +0.14$) for 100 fs and 80 fs pulses, respectively. The parameters used are $\tau_0 = 100$ *fs*, $\omega_0 = 2.36 \times 10^{15}\ s^{-1}$, λ_0–800 *nm*, $r_0 = 40$ μm, $a_{00}^2 = 6.84 \times 10^{-2}$, $n_c = 8.0 \times 10^{13}$ cm^{-3}, $n_0 = 1.8 \times 10^{22}$ cm^{-3}, $R_{C0} = 30$ *nm* and $M_i = 1.39 \times 10^{-12}$ *gm*.

pulse in comparison to $\eta = 0$ case. It is also seen that with decrease in the pulse duration the percentage variation in the growth rate of modulation instability at the front as well as at the back of the pulse decreases in comparison to the centroid of the pulse.

4. SUMMARY AND CONCLUSION

This paper deals with the analytical study of the growth rate of modulation instability as the laser pulse propagates in a clustered gas. It is shown that exponential amplitude variation ($A(\tau)$) is positive (negative) at the front (back) of the pulse due to which the growth rate of modulation instability increases (decreases) at the front (back) of the laser pulse in comparison to the centroid of the pulse. It is seen that for 100 fs (80 fs) pulse the growth rate of modulation instability at the front of the pulse increases by 4.67% (3.30%) and decreases by 4.63% (2.93%) at the back of the pulse in comparison to that of the centroid of the pulse ($\eta = 0$). Also, with decrease in the pulse duration the peak value of the growth rate of modulation instability increases and for lower (higher) values of the pulse duration change in the growth rate at the front as well as at the back of the pulse in comparison to the centroid of the pulse is reduced (enhanced). Reason for this behavior may be attributed to the fact that with decrease in pulse duration the exponential amplitude variation ($A(\tau)$) increases and the self-induced phase shift ($\Phi(\tau)$) decreases. The average enhancement in the growth rate of modulation instability at the front as well as at the back of the pulse is 73.17% by reducing the pulse duration from 100 fs to 80 fs. This analytical study shows the limitations of using short laser pulse propagating

in clustered gas since decrease in the pulse duration causes sharp rise in growth rate of modulation instability. Hence an optimum value of pulse duration may be chosen for application based on interaction of short laser pulses with clustered gas.

ACKNOWLEDGEMENT

REFERENCES

AGRAWAL, G.P. (2006). *Nonlinear Fiber Optics*. San Diego, CA: Academic.

ALEXEEV, I., ANTONSEN, T.M., KIM, K.Y. & MILCHBERG, H.M. (2003). Self-focusing of intense laser pulses in a clustered gas. *Phys. Rev. Lett.* **90**, 103402/1–4.

ANTONSEN JR., T.M. & MORA, P. (1993). Self-focusing and Raman scattering of laser pulses in tenuous plasmas. *Phys. Fluids B* **5**, 1440–1452.

BOGGIO, J.M.C., TENEBAUM, S. & FRAGNITO, H.L. (2001). Amplification of broadband noise pumped by two lasers in optical fibers. *J. Opt. Soc. Am. B* **18**, 1428–1435.

BORGHESI, M., CAMPBELL, D.M., SCHIAVI, A., WILLI, O., GALIMBERTI, M., GIZZI, L.A., MACKINNON, A.J., SNAVELY, R.D., PATEL, P., HATCHETT, S., KEY, M. & HAZAROV, W. (2002). Propagation issues and energetic particle production in laser plasma interactions at intensities exceeding 1019 W/cm^2. *Laser Part. Beams* **20**, 31–38.

BORISOV, A.B., LONGWORTH, J.W., MCPHERSON, A., BOYER, K. & RHODES, C.K. (1996). Dynamical orbital collapse drivers super X-ray emission. *J. Phys. B: At. Mol. Opt. Phys.* **29**, 247–255.

CLARK, D.S. & FISCH, N.J. (2005). Raman laser amplification in preformed and ionizing plasmas. *Laser Part. Beams* **23**, 101–106.

DITMIRE, T., DONNELLY, T., RUBENCHIK, A.M., FALCONE, R.W. & PERRY, M.D. (1996). Interaction of intense laser pulses with atomic clusters. *Phys. Rev. A* **53**, 3379–3402.

DITMIRE, T., ZWEIBACK, J., YANOVSKY, V.P., COWAN, T.E., HAYS, G. & WHARTON, K.B. (1999). Nuclear fusion from explosions of femtosecond laser heated deuterium clusters, *Nat.* **398**, 489–492.

DONNELLY, T. D., DITMIRE, T., NEUMAN, K., PERRY, M.D. & FALCONE, R.W. (1996). High order harmonic generation in atom clusters. *Phys. Rev. Lett.* **76**, 2472–2475.

ESAREY, E., SCHROEDER, C.B. & LEEMANS, W.P. (2009). Physics of laser-driven plasma-based electron accelerators. *Rev. Mod. Phys.* **81**, 1229–1285.

ESAREY, E., SPRANGLE, P., KRALL, J. & TING, A. (1996). Overview of plasma based accelerator concepts. *IEEE Trans. Plasma Sc.* **24**, 252–288.

GILL, T. S., MAHAJAN, R. & KAUR, R. (2010). Relativistic and ponderomotive effects on evolution of laser beam in a non-uniform plasma channel. *Laser Part. Beams* **28**, 11–20.

GUERIN, S., MORA, P. & LAVAL, G. (1998). Parametric instabilities due to relativistic electron mass variation. *Phys. Plasmas* **2**, 2807.

GUPTA, A., ANTONSEN JR., T.M. & MILCHBERG, H.M. (2004). Propagation of intense short laser pulses in a gas of atomic clusters. *Phys. Rev. E* **70**, 046410/1–12.

HAGENA, O.F. & OBERT, W. (1972). Cluster formation in expanding supersonic jets: effects of pressure, temperature, nozzle size and test gas. *J. Chem. Phys.* **56**, 1793–1802

JHA, P., KUMAR, P., RAJ, G. & UPADHYAYA, A.K. (2005). Modulation instability of laser pulses in magnetized plasma. *Phys. Plasmas* **12**, 123104/1–6.

JHA, P., SINGH, R.G. & UPADHYAY, A.K. (2009). Pulse distortion and modulation instability in laser plasma interaction. *Phys. Plasmas* **16**, 013107/1–5.

KIRZ, J., JAKOBSEN, C. & HOWELLS, M. (1995). Soft X-ray microscopes and there biological applications. *Quar. Rev. Biophys.* **28**, 33–130.

KLINE, J.L., MONTGOMERY, D.S., ROUSSEAUX, C., BATON, S.D., TASSIN, V., HARELIN, R.A., FLIPPO, K.A., JOHNSON, R.P., SHIMADA, T., YIN, L., ALBRIGHT, B.J., ROSE, H.A. & AMIRANIOFF, F. (2009). Investigation of stimulated Raman scattering using a short pulse diffraction limited laser beam near the instability threshold. *Laser Part. Beams* **27**, 185–190.

KUBIAC, G.D., BERNARDEZ, L.J., KRENZ, K.D., CONNELL, D.J.O., GUTOWSKI, R. & TODD, M.M. (1996). Debris-free EUVL sources based on gas jets. *OSA Trends Opt. Photon. Ser.* **4**, 66–71.

KUMARAPPAN, V., KRISHNAMURTHY, M. & MATHUR, D. (2001). Asymmetric high-energy ion emission from argon clusters in intense laser fields. *Physi. Rev. Lett.* **87**, 085005/1–4.

LIU, S.Q., TANG, W. & LI, X.Q. (2011). Modulation instability of an intense laser beam in an unmagnetized plasma. *J. Korean Phys. Soc.* **59**, 2727–2733.

MARTIJN DE STEREKE, C. (1998). Theory of modulation instability in fiber Bragg gratting. *J. Opt. Soc. Am. B* **15**, 2660–2667.

MAX, C.E., ARONS, J. & LANGDON, A.B. (1974). Self-modulation and self-focusing of electromagnetic waves in plasmas. *Phys. Rev. Lett.* **33**, 209–212.

MCKINSTRIE, C.J. & BINGHAM, R. (1992). Stimulated Raman forward scattering and the relativistic modulational instability of light waves in rarefied plasma. *Phys. Fluids B* **4**, 2626–2633.

MISHRA, R. K. & JHA, P. (2011a). Effect of chirping on the intensity profile and growth rate of modulation instability of a laser pulse propagating in plasma. *Laser Part. Beams* **29**, 259–263.

MISHRA, R.K. & JHA, P. (2011b). Effect of Coulombic expansion on the evolution characteristics of short laser pulses propagating in clustered gas. *Phys. Plasmas* **18**, 083111/1–5.

MORI, W.B. (1997). The physics of nonlinear optics of plasmas at relativistics intensities for short-pulse lasers. *IEEE J. Quantum Elect.* **33**, 1942–1953.

PHILLIPS, C.R. & FEZER, M.M. (2010). Stability of the singly resonant optical parametric oscillator. *J. Opt. Soc. Am. B* **27**, 2687–2699.

RAJA, R.V.J., PORSEZIAN, K. & NITHYANANDAN, K. (2010). Modulational-instability-induced super-continuum generation with saturable nonlinear response. *Phys. Rev. A* **82**, 013825/1–6.

SARMA, A.K. & SAHA, M. (2011). Modulational instability of coupled nonlinear field equations for pulse propagation in a negative index material embedded into a Kerr medium. *J. Opt. Sc. Am. B.* **28**, 944–948.

SARMA, A.K. & KUMAR, P. (2012). Modulation instability of ultra short pulses in quadratic nonlinear media beyond the slowly varying envelop approximation. *Appl. Phys. B* **106**, 289.

SARMA, A.K. (2010). Modulation instability of a few-cycle pulses in optical fibers. *Euro Phys. Lett.* **92**, 24004/1–4.

SHAO, Y.L., DITMIRE, T., TISCH, J.W.G., SPRIGATE, E., MARANGOS, J.P. & HUTCHINSON, M.H.R. (1996). Multi keV electron generation in the interaction of intense laser pulses with Xe-clusters. *Phys. Rev. Lett.* **77**, 3343–3346.

SPRANGLE, P., ESAREY, E. & HAFIZI, B. (1997). Intense laser pulse propagation and stability in partially stripped plasmas. *Phys. Rev. Lett.* **79**, 1046–1049.

SPRANGLE, P., HAFIZI, B. & PENANO, J.R. (2000). Laser pulse modulation instabilities in plasma channel. *Phys. Rev. E* **61**, 4381–4393.

STRIKLAND, D. & MOUROU, G. (1985). Compression of amplified chirped optical pulses. *Opt. Commun.* **56**, 219–221.

SUDO, S., ITOH, H., OKAMOTO, K. & KUBODERA, K. (1989). Generation of 5 THz repetition optical pulses by modulation instability in optical fibers. *Appl. Phys. Lett.* **54**, 993–994.

TAGUCHI, T., ANTONSEN JR., T.M., PALASTRO, J., MILCHBERG, H. & MIMA, K. (2010). Particle in cell analysis of a laser cluster interaction including collision and ionization processes. *Opt. Expr.* **18**, 2389–2405.

ZHANG, L., FU, X., DENG, J., ZHANG, J., WEN, S. & FAN, D. (2011). Role of chirp in spatiotemporal modulation instability of broadband pulsed laser. *J. Opt.* **13**, 015230/1–7.