Vol 11 No 1, January 2002
1009-1963/2002/11(01)/0050-04
Chinese Physics
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and IOP Publishing Ltd

Stimulated Raman backscattering from an ultrashort laser interacting with underdense plasmas*

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(Received 28 March 2001; revised manuscript received 9 September 2001)

We present experimental results of the stimulated Raman backscattering instability (BSRS) in an ultrashort intense (45fs, $5.7\times10^{17}\mathrm{Wcm}^{-2}$) laser pulse interacting with an optically ionized helium gas. We have studied the stimulated Raman backscattering reflectivity and the phenomenon of the transition from strongly coupled BSRS to weakly coupled BSRS. We have obtained a good agreement between our experimental results and the theory of BSRS.

Keywords: laser–plasma interactions, stimulated Raman backscattering
PACC: 5240, 4265C

1. Introduction

Stimulated Raman scattering (SRS) parametric instability is a wave–wave interaction process in which an incident electromagnetic wave (ω_0, k_0) decays into a longitudinal electrostatic wave $(\omega_{\mathrm{es}}, k_{\mathrm{es}})$ and a scattered electromagnetic wave (ω_1, k_1). SRS has long been a topic of interest in laser-driven inertial confinement fusion,[1] and it can significantly reduce the efficiency of short-pulse laser applications such as X-ray lasers,[2] wake-field generation,[3] or high-harmonics generation.[4] The stimulated Raman backscattering (BSRS) instability is also very similar to the free-electron laser (FEL) instability, and some aspects of the self-amplified spontaneous emission FEL physics can be studied in the BSRS experiment.[5] Thus, it is very important to obtain a better understanding of the SRS instability. With the rapid advance in table-top ultrashort lasers, experimental studies of SRS with short laser pulse ($\ll$1ps) have proven to be very useful since, in this regime, the instability may not have enough time to reach a nonlinear state and a direct comparison between experiments and the linear theory of the instability is possible. When the pulse length is much shorter than 100fs, such as in our experiment, the convectively unstable ionization scattering instability (ISI),[6] which will strongly scatter the pump laser and complicate the explanation of the observed phenomena, will also be greatly reduced. This will provide us with a clearer background for the experiment. On the other hand, the optical field ionization (OFI) generates plasmas with an anisotropic electron temperature distribution in the initial stage, while the existing relevant SRS theory is based on the assumption of thermal equilibrium. Therefore, the validity of the initial transient theory of SRS also needs to be demonstrated experimentally in these ultrashort pulse ($\ll$100fs) OFI laser–plasma interactions.

Previous experiments of a short-pulse laser interacting with gas or plasma have revealed different aspects of SRS. Strongly coupled SRS from 800fs laser–plasma interactions has been observed,[7] where backscattered spectra have widths larger than the plasma frequency. The experiment performed with a 500fs laser focused onto a preformed plasma has demonstrated the validity of the linear theory of SRS in the weakly coupled regime.[8]

In this paper, we report on the BSRS measurements in the underdense plasmas produced from ultrashort laser pulses interacting with an optically ionized helium gas-jet target. For the first time, as far as we know, the transition from strongly to weakly coupled SRS was observed with an ultrashort (45fs) laser pulse. The relationships between the BSRS reflectivity and the pump laser energy were also measured.

2. Experiment

*Project supported by the National Natural Science Foundation of China (Grant No. 69678012), and the National High Technology Development Programme of China (Grant No. 863-416-3).

The experiment was performed at the Laboratory for High Intensity Optics, Shanghai Institute of Optics and Fine Mechanics (SIOFM), with a Ti:sapphire laser facility[9] operating at 790nm in the chirped-pulse amplification (CPA) mode. This laser provided 45fs pulses with a 22nm full width at half maximum (FWHM) at 10 Hz, and the peak power reached 2TW. The experimental set-up is shown in Fig.1. The energy of the output laser beam in a diameter of 50mm varied from 20 to 80mJ in our experiment. A 45° coated plate which had a high reflectivity at 780–800nm reflected the laser beam into the vacuum chamber. To avoid the laser pulse expansion caused by nonlinear dispersion response while the ultrashort intense pulses propagated in the lens, we used a reflective system to focus the laser beam. For the same reason a MgF_2 plate was placed at the entrance of the vacuum chamber, which had the lowest effect on the duration of the pulse. In the chamber, the laser beam was focused with a $f/3$ 16° off-axis parabola mirror (the focal length f is equal to 15cm) onto the target. Under vacuum, the focal spot profile was Gaussian with a radius at $1/e^2$ in intensity w_0=10μm. The peak laser intensity reached 5.7×10^{17}Wcm^{-2}. A gas jet made of piezoelectric ceramic fixed on a five-dimensional gimbal mount was used to produce the ultrasonic gas blast. The gas density could be controlled by the gas background pressure P (0–300kPa) and the jet slaving voltage V (0–200V). The vacuum chamber was designed for a high vacuum of 10^{-4}Pa. In order to increase the laser–plasma interaction range and, at the same time, improve the homogeneity of the density distribution, we attached a glass tube with a length L_t ≤2.0mm and diameter ϕ=1mm to the nozzle of the gas jet. The laser beam was focused at the entrance of the tube. The backscattered light was collected by a lens behind the 45° coated plate and coupled into the fibre of a detector. A 12-bit charge-coupled device (CCD) array spectrometer with a spectral resolution of 0.35nm in the range of 650–1100nm was used to measure the reflected and transmitted spectra, and the sensitivity of the measuring system was carefully calibrated with a standard tungsten halogen light source. The synchronism between the gas jet and the laser was an important step to the experiment. We used the inset clock electrical pulse of the laser as an origin signal to trigger the gas jet with a proper time delay and electro-optical isolation. Adjusting the delay time, when the different devices worked synchronistically we could see the discharge under the jet. The gas used in our experiment was He.

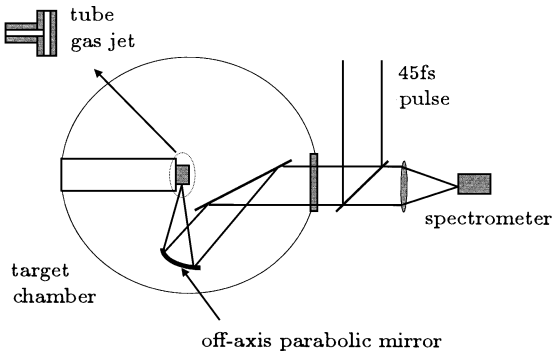


Fig.1. Experimental set-up.

3. Experimental results and analysis

The space and time behaviours of parametric instabilities for a finite pump wave duration in a bounded plasma have been extensively described.[5,10,11] A one-dimensional (1D) geometry is used in which the waves propagate in an underdense homogeneous plasma of finite length L; the space and time evolutions of the daughter waves are solved by assuming that the instability grows from thermal noise. The actual incident pulse of a characteristic duration t_p is replaced by an effective square pulse of intensity I_0 and duration $t_0 = t_p - t_{He^{2+}}$, where $t_{He^{2+}}$ is the time at which the helium gas is fully ionized.

In the weakly coupled regime, the instability has its largest growth rate when (ω_1, k_1) and (ω_{es}, k_{es}) satisfy their respective dispersion relations. Consequently, for $k_{es}^2\lambda_D^2 < 1$ and $\omega_p \ll \omega_0$, the peak of the backscattered spectrum is redshifted by the Bohm–Gross frequency

$$\omega_{BG} = \omega_p\left(1 + \frac{12\omega_0^2}{\omega_p^2} \times \frac{kT_e}{m_e c^2}\right)^{1/2}, \qquad (1)$$

where T_e is the electron temperature, and λ_D is the Debye length. Furthermore, the spectral half-width satisfies $(\Delta\omega/c) = (2\gamma/s_0)^{1/2}$ (γ is the maximum temporal growth rate in the co-moving with the speed of light coordinate, and $s_0 = ct_0$ is the laser pulse length), where $\Delta\omega$ is smaller than ω_p.[5,7] In the weakly coupled regime an inequality must be satisfied

$$I_{14}\lambda^2 < 3.64 \times 10^5 (n/n_c)^{1/2} \times \frac{1-(n/n_c)^{1/2}}{\{(1-n/n_c)^{1/2} + [1-2(n/n_c)^{1/2}]^{1/2}\}^2}, \qquad (2)$$

where n_c is the critical electron density, I and λ are laser intensity and wavelength, respectively, and $I_{14}\lambda^2$ denotes the laser flux in units of $10^{14}\mathrm{Wcm}^{-2}\mu\mathrm{m}^2$.

When the characteristic growth rate of the instability is greater than the longitudinal wave frequency, $\gamma_0 \gg (3^{3/2}/4)\omega_{es}$, the instability is said to be strongly coupled.[10] The strongly coupled stimulated Raman backscattering has been observed from the interaction of an intense 0.8ps laser with an underdense plasma. So far, to the best of our knowledge, there has been no quantitative theoretical description of the transition between strong and weak coupling in the initial phase of SRS in which the unstable waves start to grow from thermal equilibrium.

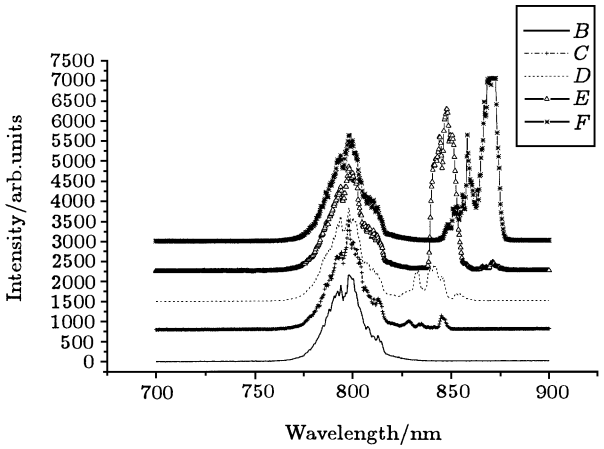


Fig.2. Experimentally observed BSRS spectra. The laser intensity is $5.7\times10^{17}\mathrm{Wcm}^{-2}$, and from B to E the electron densities are $0,4.8\times10^{18}$, 5.9×10^{18}, 7.6×10^{18}, $14.3\times10^{18}\mathrm{cm}^{-3}$ respectively.

In our experiment, the laser intensity is always greater than $5\times10^{16}\mathrm{Wcm}^{-2}$. Since the laser intensity required to yield He^{2+} is $9\times10^{15}\mathrm{Wcm}^{-2}$, the gas undergoes a rapid ionization right at the leading edge of the pulse so that the subsequent interaction is that of an intense pulse with an underdense plasma. In Fig.2, we show the experimentally observed BSRS spectra at different electron densities when the laser intensity is $5.7\times10^{17}\mathrm{Wcm}^{-2}$. As can be seen, at high electron density the inequality (2) is satisfied and the BSRS is in the weakly coupled regime. With the decrease of the electron density, the inequality (2) is no longer satisfied and the BSRS instability is translated to be strongly coupled. According to Eq.(1), the electron density of the plasma can be deduced from the frequency shift of the BSRS spectra. In Fig.2, the electron density of the transition from strongly to weakly coupled BSRS is about $7\times10^{18}\mathrm{cm}^{-3}$, while the theoretical criterion of electron density from Eq.(2) is $3\times10^{18}\mathrm{cm}^{-3}$. Considering the error caused by the uncertainty of the wavelength shift in the experimental BSRS spectra, the experimental result is in good agreement with the theory. In Fig.3, the Gaussian fits of the experimental spectra with a nonlinear least-squares algorithm[12] are given. It is obvious that the higher the electron density, the narrower the width of the spectrum; this agrees well with the theoretical description.[7] The blueshift associated with the ionization process will modify the laser spectrum during its propagation in the plasma;[13] this may also alter the backscattered spectra. Considering that the modulation of the laser pulse associated with the ionization process is characterized by a gradual steepening of the pulse front[14] where SRS is very weak, and if the broadening of the BSRS spectra were induced by the ionization process, then with the higher electron density, the width of the BSRS spectrum should also be broader because the ionization blueshift is proportional to the gas density. This is in contrast to the experimental results. So we conclude that the variation of the width of the BSRS spectra is mainly due to the transition of BSRS instability from strong to weak coupling.

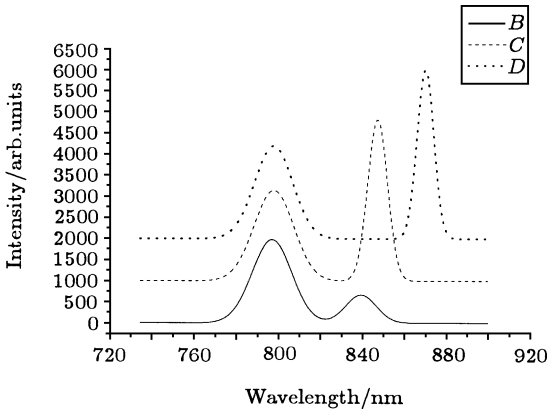


Fig.3. The Gaussian fits of the experimental spectra with a nonlinear least-squares algorithm. From B to D, the electron densities are 5.9×10^{18}, 7.6×10^{18} and $14.3\times10^{18}\mathrm{cm}^{-3}$, and the scattering peak centres are at 838, 845 and 868nm, respectively. The corresponding FWHMs of the BSRS spectra are 14.9, 9.6 and 8.2nm.

We have measured the relative time-integrated SRS reflectivity as a function of laser intensity at constant electron density, as shown in Fig.4. According

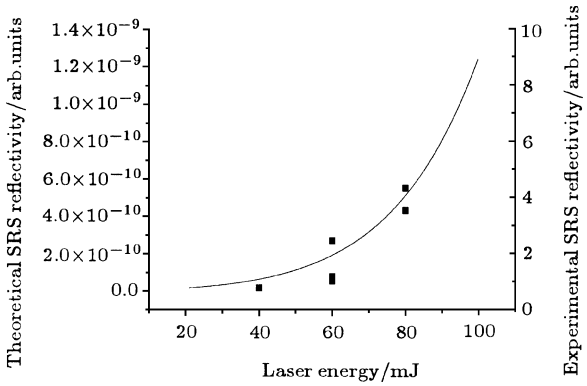


Fig.4. The time-integrated SRS reflectivity as a function of laser intensity for T_e=15eV, L=800μm, and n_e=8.1×10^{18}cm^{-3}: solid line, theoretical results; squares, experimental data.

to the wavelength shift in the BSRS spectra, the electron density of an OFI plasma is 8.1×10^{18}cm^{-3}, in which the BSRS instability is in the weakly coupled regime. The theoretical curve[10] is also plotted in Fig.4 for comparison. The electron temperature T_e and the interaction range L are chosen to be T_e=15eV and L=2R_L=800μm, respectively, where R_L is the Rayleigh length of the focused beam. To avoid the uncertainty caused by the reduction of the pump laser intensity due to ISI and the possible increase of the background thermal noise due to the anisotropy of the OFI plasma electron temperature, a relative time-integrated SRS reflectivity has been used for comparison with the theoretical prediction. As Fig.4 shows, the tendency of the experimental BSRS reflectivity agrees well with the theoretical curve.

4. Summary

We have studied the SRS instability of an ultrashort intense laser pulse interacting with a helium gas jet under various experimental conditions. We have found that, even in such an ultrashort pulse, the SRS reflectivity is still in good agreement with the initial transient stage theory of SRS starting from thermal equilibrium noise. The experimental phenomenon of transition from strongly to weakly coupled SRS was observed, and the BSRS spectrum profile was in qualitative agreement with the SRS theoretical prediction.

We would like to acknowledge the technical assistance of the laser facility staff at SIOFM during this experiment.

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