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THE TRAPPED PARTICLE SIDEBAND INSTABILITY OBSERVED IN LASER-PLASMA ACCELERATOR EXPERIMENTS

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1. Introduction

Wave-particle interactions are essential processes in plasma physics. Trapping of electrons in the field of a large-amplitude plasma waves has a significant influence on the stability of the wave itself, because the trapping induces various instabilities [1]. The trapped electrons oscillate in the potential troughs of the wave at a bounce frequency $\omega_B=(ek_pE_s/m)^{1/2}$, where E_s and k_p are the amplitude of the electrostatic field and the wavenumber of the plasma wave, and e and m are the electron charge and mass, respectively. The sidband instability is a universal phenomenon in wave-particle interactions, for example, in traveling wave tubes, a free-electron lasers, electron-beam produced plasmas and laser produced plasmas. The sideband instability for large-amplitude electrostatic waves in a plasma has been theoretically investigated, using the trapped macroparticle model, by Kruer et al [2]. Recently, a relativistic plasma wave (RPW), of which the phase velocity is fairly close to the speed of light, has been studied extensively because it is capable of accelerating electrons up to an energy range of multi-MeV over very short distances. The trapped electrons are also cause of the sideband instability. In this paper, we present the first observation of the sideband instability of self-trapped electrons in a RPW. The spectra of both the plasma wave and sideband waves are obtained with laser light transmitted through the plasma. The RPW has a phase velocity v_ϕ near the group velocity v_g of the laser pulse and its velocity is also near the speed of light c. The RPW traps background electrons by coupling with backward stimulated

Raman scattering. The trapped electrons copropagate with both the RPW and the laser pulse. The interaction of trapped electrons with the RPW generates sideband plasma waves.

2. Experimental observation

The experiment was performed with a 2-TW Ti:sapphire laser. The details of the experimental setup and procedure have been presented in Ref.[3,4]. The experimental parameters are briefly summarized here. The center wavelength was 800nm, i.e., the angular frequency $\omega_l = 2.36\times10^{15}\mathrm{s}^{-1}$. The laser beam was focused on a nitrogen gas jet by an off-axis parabolic mirror with *f*/3.3. The spot diameter was 5μm at the full-width at half-maximum. The laser peak intensity was estimated to be $5\times10^{18}\mathrm{W/cm}^2$, corresponding to the normalized vector potential a_0=1.5. The molecular density at the gas-jet center was estimated to be $1.5\times10^{19}\mathrm{cm}^{-3}$.

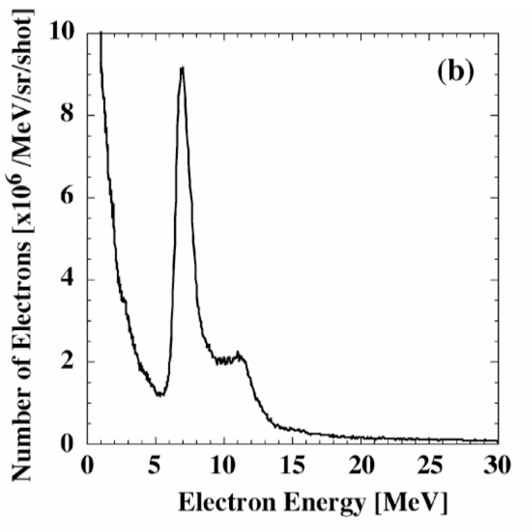

Fig.1 Typical energy spectrum of the electron beam.

The energy spectrum of accelerated electrons, which were accelerated to relativistic energies, is shown in Fig.1.

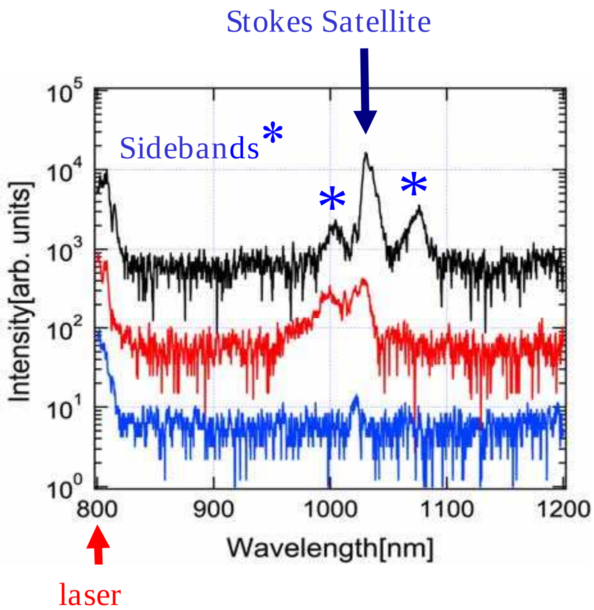

Fig.2 Spectrum of forward Raman scattering.

Figure 2 shows the frequency spectrum near the forward Raman Stokes frequency for three different laser shots. The forward Raman Stokes center frequency was $\omega_s = 1.82\times10^{15}\mathrm{s}^{-1}$. The plasma frequency corresponds to the Stokes frequency $\omega_p = \omega_l - \omega_s \cong 5.3\times10^{14}\mathrm{s}^{-1}$, namely, $\omega_p/\omega_l \cong 0.23$. The plasma density of the region where the plasma wave was strongly excited was estimated to be $8.8\times10^{19}\mathrm{cm}^{-3}$ without a relativistic correction. On the other hand, taking into account the relativistic correction, i.e., $\omega_p = (4\pi e^2 n_e/m_0)^{1/2}\gamma_a^{-1/2}$, $n_e \cong 1.3\times10^{20}\mathrm{cm}^{-3}$. Here, $\gamma_a = (1+a_0^2/2)^{1/2} \cong 1.5$ is a relativistic factor corresponding to the electron motion in the

relativistic laser field and m_0 is the electron rest mass. The plasma wave can be excited due to either self-modulation (SM) or forward Raman scattering (FRS), because $\Gamma_{RS}/\Gamma_{SM}\cong 1$. The plasma wave has a phase velocity v_ϕ near the group velocity v_g of the laser pulse, $v_\phi \cong v_g = c(1-(\omega_p/\omega_l)^2)^{-1/2}$. The plasma wave is capable of accelerating trapped electrons.
Stokes satellite is accompanied by secondary wings (sidebands) in the upper trace in Fig.1.

The frequencies of upper and lower sidebands on the forward Raman spectrum were ω= $1.75\times10^{15}\text{s}^{-1}$ and ω= $1.88\times10^{15}\text{s}^{-1}$, respectively. Here, the frequency separation $\Delta\omega$ of the sidebands from the large amplitude plasma wave is given by $\Delta\omega_\pm = |\omega_p - \omega_\pm| \cong 6.3\times10^{13}\text{s}^{-1}$, namely, $\Delta\omega/\omega_p \cong \Delta\omega_\pm/\omega_p \cong 0.12$. There is asymmetry in the profile of the frequency separation between the upper and lower spectra. The value of $\Delta\omega_\pm$ has an ambiguity of 20%. The sideband spectrum suggests that there are two satellite plasma waves ($\omega_p \pm \Delta\omega_\pm$, $\boldsymbol{k}_\pm$ other than the fundamental wave and satellite plasma waves (ω_p, $\boldsymbol{k}_p$, where $\boldsymbol{k}_p$ and $\boldsymbol{k}_\pm$ show wavenumber of the fundamental wave and satellite plasma waves, respectively. The width of frequency separation is related to the amplitude of the fundamental plasma wave [4].

3. Discussions

The growth rate of the sideband instability has been investigated, through the analysis of the dispersion relation for large-amplitude plasma waves based on the macroparticle model [2] and for free electron lasers by Lin [5]. We derived the dispersion relation of the sideband instability for RPW under an intense electromagnetic field following the approach in Ref.[2]. For simplicity, we use the following two assumptions that the trapped electron has a constant energy, $(\gamma_\phi-1)^2)mc^2$, where $\gamma_\phi=(1-(v_\phi/c)^2)^{-1/2}$ is a relativistic factor corresponding to the phase velocity of the plasma wave, and that the background electrons move collectively in the averaged relativistic laser field. We obtain a dispersion relation similar to Eq.(7) in Ref.[2], with the exceptions that $\omega_B=(ek_pE_s/\gamma_\phi^3 m_0)^{1/2}$ and $\omega_p^2=\omega_{p0}^2/\gamma_a$. The dispersion relation of RPW has two features which originate from two relativistic effects the trapped electrons have relativistic energies and the background electrons are affected by the relativistic laser field which drives the plasma wave.

The dispersion relation has four independent parameters: ω_B/ω_{p0}, n_b/n_e, v_t/v_ϕ and γ_a, where n_b is the number density of the trapped electrons and v_t is the thermal velocity of the background plasma. By adjusting these parameters, we found a solution that satisfies two requirements that the frequency separation $\Delta\omega/\omega_p \cong 0.12$ and that the two sidband waves have velocities almost equal to that of the fundamental plasma wave $v_\phi \sim v_g \sim 0.974c$. According to the width of the sideband spectra observed experimentally, $n_b/n_e \cong 1\times10^{-4}$, $\gamma_a\sim 1.35$, $v_t/v_\phi \cong 0.1$ and the growth rate $\Gamma \cong 0.02\omega_{p0}$, which corresponds to the spatial growth rate Γ_L=0.03/μm. With the interaction length L_I=500μm determined from the side-scattering image, we obtain e-folding growth factor $\Gamma_L L_I \cong 15$. for our experimental conditions. . The experimentally observed sideband frequencies (upper) ω are shown in Fig.3 (*), corresponding to the peaks of the growth rate (lower) Γ. We find a reasonable agreement between the experimental observation and the model prediction.

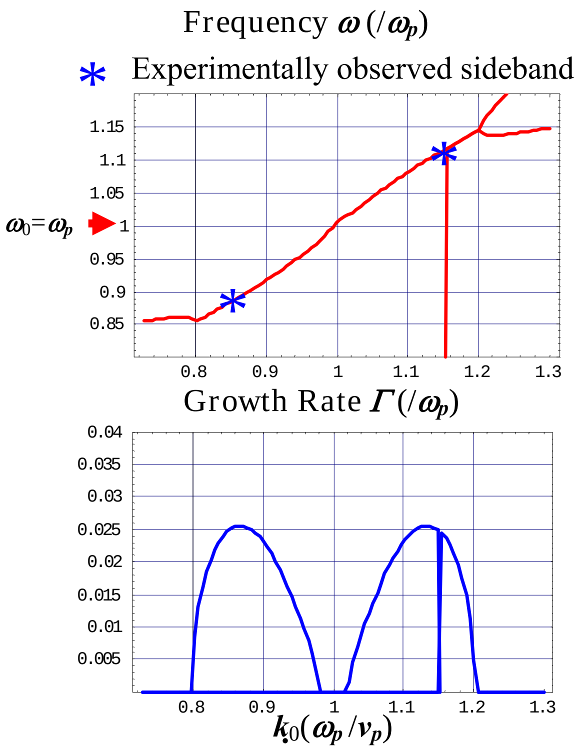

Fig.3. Frequency and growth rate of sideband instability.

4. Conclusion

We found evidence of the presence of a trapped-particle sideband instability in a RPW in laser-plasma acceleration experiments, for the first time, through the observation of the transmitted light spectrum and electron energy spectrum. Using the simple macroparticle model, we showed that the sideband instability in the RPW is one of the physical mechanisms that can explain the experimental results. The large-amplitude RPW excited by an intense laser pulse would be useful tool for investigating the interaction of high-energy electrons with the relativistic plasma wave in high-energy plasma physics.

References

[1] W.L.Kruer, *The Physics of Laser Plasma Interactions* (Frontiers in Physics) , Westview Press, California, 1988.

[2] W.Kruer , Dawson and Sudan, Phys. Rev. Lett. 23, 838 (1969).

[3] E.Miura, K.Koyama, S.Kato, N.Saito, M.Adachi, Y.Kawada, T.Nakamura and M.Tanimoto, Appl. Phys. Lett. 86, 251501 (2005).

[4] K.Koyama, M.Adchi, E.Miura, S.Kato, S.Masuda, T.Watanabe, A.Ogata and M.Tanimoto, Laser and Particle Beams, 24, 95 (2006).

[5] A.T.Lin, Phys. Rev. Lett. 46,1515 (1981).