Plasma slab radiating pseudo-cavity mode in SRS-like behaviour for frequency difference less than the plasma frequency : KEEN-type mode in relativistically hot plasma

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PIC simulation work has been recently published by Nikolic et al. [1] using on the interaction of very intense laser light with a moderately dense plasma slab $\left(n_0/n_c = 0.6, 0.4\right)$. ($n_c$ is the electron density value such that, the plasma frequency corresponding to n_c, is equal to ω_0, the incident (laser) wave frequency). These values were so chosen $\left(\text{i.e.}, n_0 \geq 0.25 n_c\right)$ as to make the usual plasma SRS (Stimulated Raman Scattering) impossible in order to avoid its complications. This was interpreted as possible stimulated narrow-band scattering from long-lived electrostatic excitations at phase velocities comparable to electron thermal velocities and frequencies considerably less than ω_{pr}, a phenomenon termed [2] SEAS (for Stimulated Electron Acoustic Scattering) by Montgomery et al.. ω_{pr} $\left(\omega_{pr} = \omega_p \sqrt{\langle 1/\gamma \rangle}\right)$ is the relativistic plasma frequency, ω_p being the classical plasma frequency corresponding to $n_0 . \gamma$ is the relativistic factor. As has been found in other Vlasov simulations [3] while excitations in this frequency and phase velocity range can be produced if coherently driven up to self-sustained levels, these excitations are fundamentally nonlinear (being termed KEEN waves for Kinetic Electrostatic Electron Nonlinear waves) and may be excited in a large band gap. Now, as remarked before [2], the lack of low-level narrow-band resonance precludes the usual stimulated scattering process of three-wave resonance amplification from a low-level seed. How then could something of the SEAS character be produced in the simulations [1] that seem to lack any specific resonance of the longitudinal plasma excitation? From the work here described the answer appears to lie in the fact that the simulation plasma was in the form of a relatively sharp-edged slab and this supports a previously unrecognized electromagnetic radiating plasma pseudo-cavity mode whose wave vector is determined by the slab width and whose frequency is close to ω_{pr}. It is the beating of this slab pseudo-mode with the pump which will define the KEEN frequency of about $\left(\omega_0 - \omega_{pr}\right)$. We refer to this unusual plasma slab stimulated scattering process involving the KEEN mode as SKSS (Stimulated KEEN Slab Scattering).

A semi-Lagrangian Vlasov-Maxwell code is used with only one spatial dimension in the axial wavevector direction (the relevant phase space being $\left(x\omega_p/c, p_x/mc\right)$) and the conservation of the canonical momentum in the transverse direction. Details of the code may be found in [4]. Such a noiseless code affords the desired phase space resolution to discern the dynamics of the trapped particles. For the results discussed in this letter, the phase space sampling $N_x N_{p_x}$ is 4097×1025 and the time step $\Delta t \omega_p$ is close to 0.04. Ions are immobile. The circularly polarized electromagnetic wave propagates through a vacuum space of $40 c/\omega_p$ onto a slab of uniform plasma (slab width denoted by L_s). The laser amplitude rises approximately linearly during τ, and is then held constant during all the rest of the simulation. The main difficulty in resolving SKSS from the standard SRS in laser–plasma experiments is that the backscattered light spectrum can cover the nearly continuous broad range of frequencies. The situation may be somewhat more favourable in initially hot plasma where the growth rates of SRS are significantly reduced allowing SKSS to be the dominant mechanism. Therefore we have maintained the initial plasma temperature to $T_e = 400 keV$.

We present now in detail the result of a simulation that was performed with $n_0/n_c = 0.6$. The quiver momentum of the electron is $a_0 = 0.5$, corresponding to $0.68 \times 10^{18} Wcm^{-2}$ and $\tau = 750\omega_p^{-1}$. In this example the plasma is initially only $L_s = 60 c/\omega_p$.

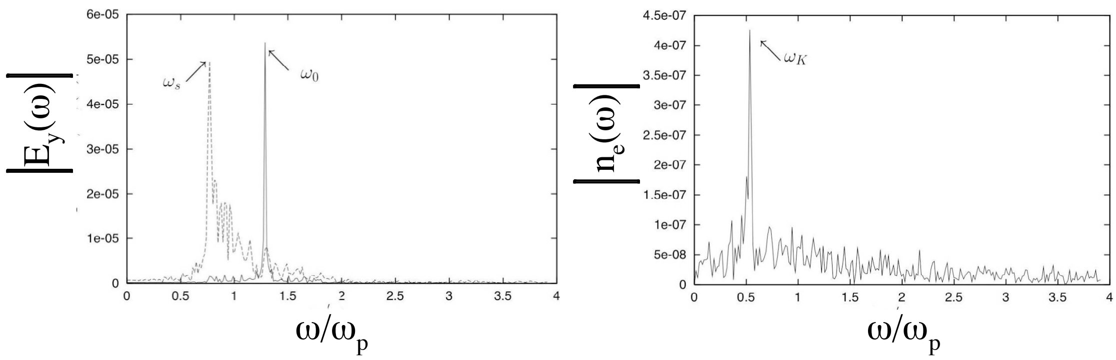

Fig. 1 : Backward (shown 20 times larger in dashed line) and forward (shown in solid line) electromagnetic (left panel) and electron density (right panel) ω-spectra.

The ω-spectra given in Fig. 1 have been obtained in the time interval $[600,1000]\omega_p^{-1}$ when SKSS is well established. A three-wave coupling mechanism was observed : a resonant three-wave parametric instability has been observed in simulation involving the incident pump electromagnetic wave (ω_0, k_0), the backscattered electromagnetic wave (ω_s, k_s) and a KEEN wave (ω_K, k_K). The resonant conditions

$$\omega_0 = \omega_s + \omega_K \text{ and } k_0 = -k_s + k_K \text{ (with } \omega_{0,s}^2 = \omega_p^2 \langle 1/\gamma \rangle + k_{0,s}^2 c^2 \text{)}$$

are well satisfied. The forward ω-spectrum of Fig. 1 exhibits clearly the peak at the pump frequency $\omega_0 = 1.290\omega_p$ (in agreement with the predicted value of $\sqrt{n_0/n_c}$ close to 1.291). The corresponding wave number k_0 was estimated close to $k_0 c/\omega_p = 1.032$. Previous values ω_0 and k_0 indeed satisfy their standard dispersion relation using $\langle 1/\gamma \rangle \cong 0.60$, estimated directly in Vlasov simulation. Fig. 1 indicates the existence of a backscattered wave at ω_s that is found to be driven near critical, i.e. $\omega_s = \omega_{pr} = 0.77\omega_p$ which implies $k_s \approx 0$. The resonant conditions are well satisfied in this simulation as shown in the right panel of Fig. 1 showing the spectrum of the electron density that clearly exhibits a peak at the expected difference KEEN frequency $\omega_K = 0.52\omega_p$ (well below ω_{pr} including relativistic and temperature effects).

The physical parameters for the code run of Fig. 2 are unchanged except that τ is taken to be $450\omega_p^{-1}$.

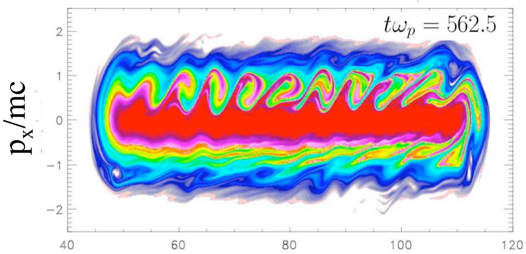

Fig. 2 : Electron phase space representation showing the SKSS development.

We see clearly nine or ten vortices for a plasma length of $9.85\lambda_0$ indicating that the longitudinal wavenumber k_K is close to the k_0 value in the plasma. As shown in the earlier phase space frame of Fig. 2, the SKSS for this hot plasma has developed. We found that strong trapping effects occur for even “small amplitude” electrostatic waves , resulting in undamped travelling waves.

We focus now on the production of SKSS for a range of plasma densities. A series of numerical simulations was carried out to confirm the existence of SKSS and the generation of KEEN waves for a wide range of values of n_0/n_c (see below Fig. 3). In these simulations, the physical parameters are unchanged from those of Fig. 2 excepted that now n_0/n_c was varied from 0.15 to 0.975. **First**, as can be seen in Fig. 3 which displays the normalized plasma phase momentum u_φ of the KEEN wave as a function of the ratio n_0/n_c , it’s possible to excite a KEEN wave over a wide range of phase velocities. The solid line was obtained by estimating u_φ directly from the SKSS scenario using the resonant conditions in frequencies and wavenumbers. We have then determined the quantity $u_\varphi = v_\varphi \gamma_\varphi / c$ by taking $v_\varphi = \omega_K / k_K \cong (\omega_0 - \omega_{pr}) / k_0$ where $\gamma_\varphi = 1 / \sqrt{1-\beta_\varphi^2}$ and $\beta_\varphi = v_\varphi / c$. The numerical estimation values obtained from the actual Vlasov simulations are represented by crosses on the curve. These values were measured by analysing the spectra in frequency and wave vector of the electromagnetic and plasma fields. The very good agreement between theoretical and numerical values tend to prove that the confined electromagnetic radiating plasma pseudo-cavity mode with the pump drives these kinetic trapped electron modes with frequency equal to $\omega_0 - \omega_{pr}$ and a wavelength of about the pump wavelength.

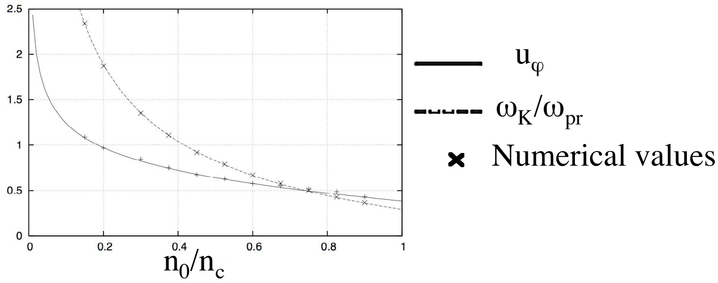

Fig. 3 : Normalized plasma phase momentum and KEEN wave frequency vs n_0/n_c.

Second, from the curve of the ratio of the KEEN wave frequency ω_K to the relativistic plasma frequency ω_{pr} as a function of n_0/n_c, given in Fig. 3 too, KEEN modes seem to be not only low frequency modes, but also for n_0/n_c typically less than 0.4 high frequency modes, this new high frequency regime precludes SEAS scenario.

References

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