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IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

LASER BEAT ACCELERATOR

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Abstract

Parallel intense photon (laser, microwave, etc.) beams ω_0, k_0 and ω_1, k_1 shone on a plasma with frequency separation equal to the plasma frequency ω_p is capable of accelerating plasma electrons to high energies in large flux. The photon beat excites through the forward Raman scattering large amplitude plasmons whose phase velocity is equal to $(\omega_0-\omega_1)/(k_0-k_1)$, close to c in an underdense plasma. The plasmon electrostatic fields trap electrons and carry them to high energies: Maximum electron energy

$$W^{max} = 2mc^2[1-(\omega_0-\omega_1)^2/c^2(k_0-k_1)^2]^{-1} \sim 2mc^2(\omega_0/\omega_p)^2 .$$

The multiple forward Raman instability produces smaller and smaller frequency and group velocity of photons; thus the photons slow down in the plasma by emitting accelerated electrons (inverse Cherenkov process).

Introduction

A plain straight waveguide sustains electromagnetic waves whose phase velocity is greater than speed of light c. Such electromagnetic waves, therefore, cannot couple to particles. If one imposes periodic structure along the propagation direction in the waveguide, the Brillouin effect on the waveguide modes makes the phase velocity of the electromagnetic waves less than c, thereby enables to couple with particles. Conventional linear accelerators employ such a method. For collective acceleration, a large flux of electrons participate and now these electrons may be regarded as plasma electrons with or without background ions. The electromagnetic waves (photons) in such a medium has a phase velocity $c/(1-\omega_p^2/\omega_0^2)^{1/2}$, again larger than c, and thus are unable to couple to and accelerate electrons, where ω_0 is the photon frequency and ω_p the electron plasma frequency. It is, however, possible to nonlinearly couple to the plasma if the amplitudes of the electromagnetic waves are sufficiently large. In Refs. 1 and 2 we discussed a laser electron accelerator scheme by exciting a large amplitude Langmuir wave created as a wake by a strong photon wavepacket with a very short spatial pulse length. We found there that the forward Raman process plays a stronger role than the backscattering. In this article we take full advantage of the forward Raman process by injecting two parallel photon beams creating a large amplitude beat plasma wave. This is to utilize free electrons (plasma electrons) nonlinearly trapped by the created electrostatic wave and, in this sense, it is an inverse process to the free electron laser.

Photon Beat Accelerator

In order to avoid the difficulty to make a very short pulse called for in Ref. 1, we propose to inject two parallel intense photons (laser, microwave, or any other relevant frequency electromagnetic waves)shone on a plasma with plasma frequency matched to the beat frequency of the two photons: $\omega_p=\omega_0-\omega_1$. The electromagnetic waves may have a very long pulse length. The two photons produce the beat plasma wave $\omega_p=\omega_0-\omega_1$ and $k_p=k_0-k_1$, where $k_p=\omega_p/c$. In an underdense plasma, the phase velocity of the beat plasma wave is very close to c: $\omega_p/k_p \simeq (\omega_0-\omega_1)/(k_0-k_1) \lesssim c$. As the electrostatic plasma wave grows and traps the bulk of electrons, the wave staturates via the enhanced Landau damping.[3] The accelerated electron energy by this mechanism is theoretically

$$W^{max} = 2mc^2[1-(\omega_0-\omega_1)^2/c^2(k_0-k_1)^2]^{-1} \sim 2mc^2(\omega_0/\omega_p)^2 , \quad (1)$$

which may be derived along the line given in Ref. 1.

Computer Simulation

We demonstrate the above concept by carrying out a particle simulation utilizing the relativistic electromagnetic particle code.[4] The code deals with a one and two halves dimensions [one position variable (x) and three velocity (v_x, v_y, v_z) and field variables]. The pump electromagnetic waves (ω_0, k_0) and (ω_1, k_1) are propagating in the positive x direction. In the particular case we show parameters are: $\omega_0=4.29\ \omega_p$, $\omega_1=3.29\ \omega_p$, the electron thermal velocity $v_{te}=1\ \omega_p\Delta$, the speed of light $c=10\ \omega_p\Delta$, the system length 1024Δ, and 10240 particles, and each beam amplitude is given as $eE_i/m\omega_i=c$ (i=0 or i=1) with Δ being the grid spacing. Figure 1(a) shows the phase space of electrons accelerated by the beat plasma wave. Instead of having a stretched phase space tongue (high energy electrons) just behind the short pulse laser packet (Ref. 1), we now have a high energy tongue in every ridge of each wavelength of the beat plasma wave. The observed maximum electron energy was 85 mc^2, which was slightly more than the theoretical value by Eq. (1). One reason why it exceeds the theoretical value may be that we have now two $eE_i/m\omega_i=c$ waves (i=0 and i=1) so that magnetic acceleration also begins to play a role.[5] The distribution function $f(p_\parallel)$ is shown in Fig. 1(b), exhibiting intense plasma heating as well as an extremely energetic tail.

Forward Raman Instability

Figure 2 shows the electromagnetic energy spectra of the system at two different times. At the earlier time the originally two-peaked (at k_0 and k_1) structure shows already a downward cascade, while some small amount of energy is up-converted. The spectrum is sharply peaked at particular discrete wavenumbers $k_n=k_0-nk_p$ where n is an integer and $k_p=\omega_p/c$. The spectral density $S(k,\omega)$ (not displayed here) for the electrostatic component shows no significant energy in any frequency at the backscatter wavenumber $k_b \cong 2\ k_0$. This strongly suggests that all possible backscattering processes are suppressed or saturated at a very low level in our present problem. The electrostatic spectral density at the resonant plasma wavenumber $k=k_p$ is very intense with some other energies at the multiple forward Raman scattering.

We believe the reason why backscattering is suppressed is the following. When the backscattering electrostatic plasma wave is excited, heavy Landau damping by this plasma wave saturates the backscattering process. The phase velocity of the plasma wave is

0018-9499/81/0600-3416$00.75©1981 IEEE

$v_p = \omega_p/2k_0 = (\omega_p/2\omega_0)$. The trapping width is given approximately by $\Delta v_t = (2eE_L v_p/m\omega_p)^{\frac{1}{2}}$, where E_L is the plasma oscillation electric field. The condition that a large number of electrons are trapped is given[3] by $v_p - \Delta v_t \simeq 0$, which yields the saturation amplitude E_{Ls} for the longitudinal wave as

$$\frac{eE_{Ls}}{m\omega_p} = \frac{c}{4}\frac{\omega_p}{\omega_0} \quad . \tag{2}$$

The forward Raman process is the last process to be saturated in this underdense plasma. It can be argued that it will saturate only when the original electromagnetic wave has completely cascaded to waves near $\omega = \omega_p$. The maximum energy conversion efficiency from the electromagnetic waves to electrostatic waves and ultimately to particle energy may be estimated as $\eta_{max} = 1 - (\omega_p/\omega_0)^2$. If two dimensional effects are taken into consideration, side scattering comes in as well as self-focusing, which make the detailed analysis much more complex.

Experimental Support

An experimental observation of the forward Raman process (instability) and associated electron acceleration/heating has recently been done[6] in conjunction with the above concept and simulation: a CO_2 laser is shone on an underdense plasma producing about 1.3 MeV electrons with $eE_0/m\omega_0 c$ 0.3 and $n/n_c = 0.22$. In the experiment the laser emits only one beam so that the beat has to grow from the noise. It is, therefore, in general possible to have other competing processes such as side scatter, backscatter, two plasmon decay simultaneously taking place. In spite of these competing processes, lower quivering velocity of the laser, and (lower ω_0/ω_p, the experiment shows high energy electrons.

Conclusions

A much larger flux of accelerated electrons (much higher luminocity) and somewhat more energetic electrons can be produced by the present laser beat accelerator than by the original concept of the laser electron accelerator.[1,2] The laser beams may be replaced by other electromagnetic waves of an appropriate frequency for a different plasma density. The unwanted instability effects such as side scattering may be adequately handled by this two-beam resonance.

Acknowledgment

This work was supported by U.S. Department of Energy grant number DE-FG05-80ET 53088 and NSF PHY79-01319.

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Figures

Fig. 1 Photon beat acceleration by two beams (ω_0, k_0) and (ω_1, k_1). (a) The electron phase space (x, p_x) at $t=240\ \omega_p^{-1}$. The maximum $\gamma_{\parallel}$ for electrons is 85 in this case. (b) The logarithm of the electron distribution function at $t=135\ \omega_p^{-1}$.

Fig. 2 The electromagnetic energy distribution as a function of mode numbers. Pumps k_0 and k_1 are indicated by arrows. (a) At $t=142.5\ \omega_p^{-1}$ and, (b) at $t=240\ \omega_p^{-1}$.

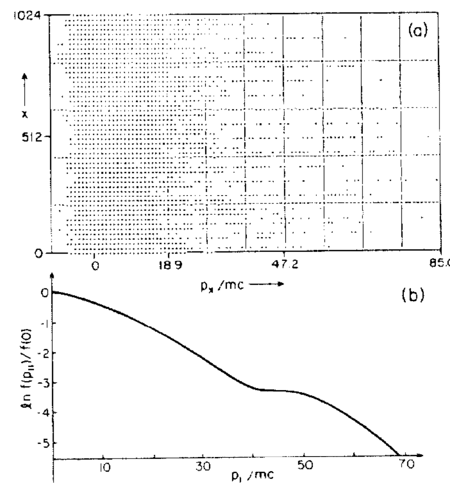

Fig. 1

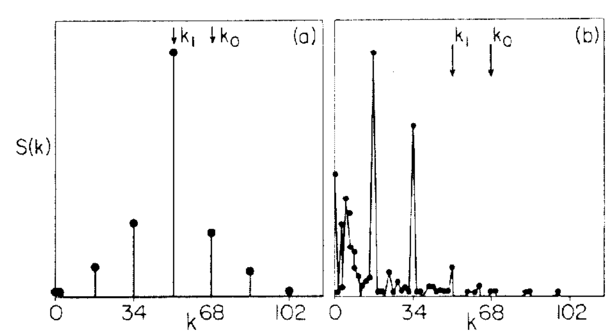

Fig. 2