ELECTRON ACCELERATION BY A WHISTLER PULSE

R. Singh, A. K. Sharma, CES, IIT Delhi, India.

Abstract

A Gaussian whistler pulse is shown to cause ponderomotive acceleration of electrons in a plasma when the peak whistler amplitude exceeds a threshold value and whistler frequency is greater than half the cyclotron frequency, $\omega > \omega_c / 2$. The threshold amplitude decreases with the ratio of plasma frequency to electron cyclotron frequency, ω_p / ω_c. The electrons gain velocities about twice the group velocity of the whistler.

INTRODUCTION

Recent advances in high power lasers have led to schemes that can produce large phase velocity plasma waves and the latter can accelerate electrons to hundreds of *MeV* energy. Since ultraintense laser pulses obtained from the chirped pulse amplification (CPA) technique became available, ponderomotive acceleration has been intensively investigated theoretically and experimentally. A fast moving electron at the front of the pulse experiences a forward ponderomotive force and can gain large energies when its velocity acquires a value greater than the group velocity of the laser before reaching the pulse peak, so that it always remains ahead of the peak.

Liu and Tripathi [1] have investigated ponderomotive effect on various acceleration schemes. Laser ponderomotive force is seen to enhance the plasma wave driven electron acceleration through the snow plough effect. Pukhov *et al.* [2] in their three-dimensional particle-in-cell (PIC) simulation of intense short laser pulse interaction with plasma have observed strong flows of relativistic electrons axially comoving with the laser pulse and generating 100 *MG* azimuthal magnetic field. The electron energies are far in excess of ponderomotive potential energy and the acceleration is a consequence of direct exchange of energy between electron and laser via betatron resonance.

Recently Sharma and Tripathi [3] have examined electron acceleration by a circularly polarized Gaussian laser pulse in magnetized plasma through Doppler shifted cyclotron resonance. The group velocity of the laser pulse is less than the speed of light and hence electrons can resonantly interact with the pulse. The gain in energy occurs when electron velocity exceeds the pulse group velocity and the electron out runs the laser pulse. The ponderomotive force of the laser is resonantly enhanced when Doppler shifted laser frequency equals the cyclotron frequency.

We analytically examine electron acceleration by the ponderomotive force associated with a right circularly polarized Gaussian whistler pulse in a magnetized plasma. Initially, the electrons have speeds lower than the group velocity of the whistler pulse and the ponderomotive force pushes electrons ahead of the pulse. The group velocity of the whistler pulse is significantly less than the speed of light and hence electrons can resonantly interact with the pulse. One expects the saturation to occur when electron velocity exceeds the pulse group velocity and the electron out runs the whistler pulse.

ANALYTICAL TREATMENT

Consider the propagation of a right circularly polarized whistler pulse in a plasma in the direction of static magnetic field $B_s \hat{z}$. The electric and magnetic fields of the whistler are

$$\vec{E} = (\hat{x} + i\hat{y}) A_0 (z - v_g t).\exp[-i(\omega t - kz)], \tag{1}$$

$$\vec{B} = -\left[\frac{1}{\omega}\left(1 - \frac{v_g k}{\omega}\right)\frac{\partial A_0}{\partial z} + \frac{ik}{\omega} A_0\right](\hat{x} + i\hat{y}), \tag{2}$$

where

$$\left(1 - \frac{v_g k}{\omega}\right) = \frac{\omega_p^2 (2\omega - \omega_c)}{2\omega(\omega - \omega_c)^2 \left(1 + \frac{\omega_p^2 \omega_c / \omega}{2(\omega - \omega_c)^2}\right)}$$

The whistler imparts oscillatory velocity to electrons,

$$\vec{v} = \frac{e\vec{E}}{mi(\omega - \omega_c)}. \tag{3}$$

Also after using iteration method, $\vec{B}$ becomes

$$\vec{B} = -\left[\frac{1}{\omega}\left(1 - \frac{v_g k}{\omega}\right)\frac{\partial A_0}{\partial z} - \frac{ik}{\omega} A_0\right](\hat{x} + i\hat{y}) e^{-i(\omega t - kz)}.$$

One obtains the parallel component of ponderomotive force (with respect to static magnetic field)

(4)

$$F_{pz} = -\frac{e^2}{2m\omega(\omega - \omega_c)} \times \frac{\omega_p^2 (2\omega - \omega_c)}{2\omega(\omega - \omega_c)^2 \left(1 + \frac{\omega_p^2 \omega_c / \omega}{2(\omega - \omega_c)^2}\right)} \frac{\partial A_0^2}{\partial z}. \tag{5}$$

One may note that F_{pz} changes sign at $\omega = \omega_c / 2$. We have chosen $\omega > \omega_c / 2$ so that the front of the whistler pulse exerts a longitudinal force on the electrons and there is net energy gain by the electrons. The equation of motion for an electron in the presence of the ponderomotive force is

$$\frac{d^2z}{dt^2} = -\frac{e^2}{2m^2\omega(\omega-\omega_c)} \times \frac{\omega_p^2(2\omega-\omega_c)}{2\omega(\omega-\omega_c)^2\left(1+\frac{\omega_p^2\omega_c/\omega}{2(\omega-\omega_c)^2}\right)}$$

$$\times\frac{A_0^2}{\tau^2}\frac{2}{v_g}\left(t-\frac{z}{v_g}\right)\exp[-(t-z/v_g)^2/\tau^2)].$$

Let us define

$$\frac{z-v_g t}{v_g\tau} = \xi,$$

$$\frac{dz}{dt} = v_g\tau\frac{d\xi}{dt} + v_g.$$

Now we calculate the electron velocity at $t=-\infty, z=0$ and $v_z = v_0$, we get $c_1 = (v_g - v_0)^2$, at $t=\infty$,

$$(v_z - v_g)^2 = (v_g - v_0)^2,$$

$$v_z = v_g \pm \sqrt{(v_g - v_0)^2},$$

$$= 2v_g - v_0, \text{ when wave amplitude is large,}$$

$$= v_0, \text{ when wave amplitude is small.}$$

Thus the electron with small v_0 (small positive initial velocity) gains less velocity (energy).

Next, we calculate the normalized threshold whistler amplitude for which $v_z = v_g$, at $\xi = 0$ i.e., electron velocity is equal to the group velocity of the whistler pulse then we get

$$a_0^2 = -\frac{(v_g - v_0)^2 \times 2(1-\omega_c/\omega)^3}{\omega_p^2/\omega^2(2-\omega_c/\omega)} \times\left(1+\frac{\omega_p^2/\omega^2(\omega_c/\omega)}{2(1-\omega_c/\omega)^2}\right)$$

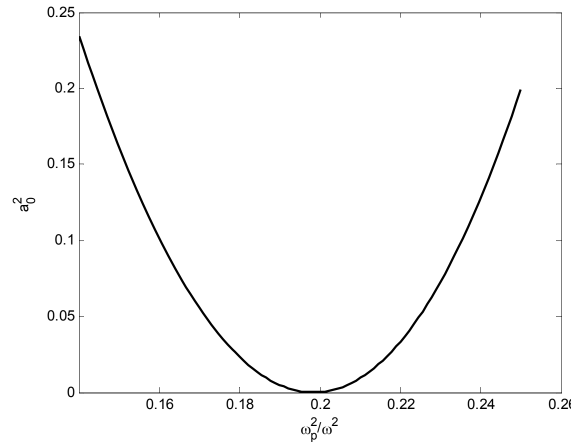

Fig. 1. Variation of normalized whistler amplitude a_0^2 with ω_p^2/ω^2 for $\omega_c/\omega = 1.3$ and $v_0 = v_g/10$.

In Fig. 1 we plot a_0^2 versus ω_p^2/ω^2 for $\omega_c/\omega = 1.3$ and 2, it is seen that the variation of a_0^2 with ω_p^2/ω^2 is in a parabolic pattern.

DISCUSSION

The ponderomotive force associated with a 1D whistler pulse is axial. For $\omega > \omega_c/2$ the ponderomotive is directed away from the intensity maximum while for $\omega < \omega_c/2$ the ponderomotive force reverses direction and tends to pull electrons towards the intensity peak. In 1D, the electron gains energy during the rising front of the pulse, the rear acts as a backward ponderomotive force and slows down the electron to its original energy. The threshold corresponds to $v_z = v_g$ at the pulse peak, i.e., the electron velocity is equal to the group velocity of the whistler pulse as the electron reaches the pulse peak.

REFERENCES

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