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Current Drive Generation Based on Autoresonance and Intermittent Trapping Mechanisms

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ABSTRACT

Two mechanisms for generating streams of high parallel velocity of electrons are presented. One has its origin in Autoresonance (AR) interaction taking place after a trapping conditioning stage, the second being dominated by the trapping itself. These mechanisms are revealed from the study of the relativistic motion of an electron in a configuration consisting of two counterpropagating electromagnetic waves along a uniform magnetic field in a dispersive medium. The operation of these mechanisms was found to circumvent the deterioration of the electron acceleration process which is characteristic for a dispersive medium, allowing for an effective generation of current drive.

The possibility to utilize electromagnetic waves in the electron cyclotron range of frequencies for heating plasmas is successfully realized in many laboratories around the world. This heating process is generally based on a resonance interaction of the electrons with some harmonics of the electron cyclotron waves. There is, however, a very powerful mechanism for transferring energy and momentum from these waves to electrons, which has drawn much less attention in the past : this is the AR interaction. When applying this AR interaction to realistic plasmas, one encounters two basic obstacles : a) the necessity of having exact appropriate initial conditions for this mechanism to be operational and b) the necessity of having the refractive index of the medium of the propagating wave equal to 1. In previous publications[1,2], we have shown that for waves propagating in the vacuum, the dephasing limitation (first obstacle) could be circumvented by introducing two circularly polarized electromagnetic waves propagating in opposite directions along a constant magnetic field. Such a configuration allows for the generation of a stochastic base, from which multiple AR accelerations can repeatedly take place and results in a velocity distribution having a high averaged velocity parallel to the magnetic field. Here, we will show that the same configuration itself can support a high averaged velocity parallel to the magnetic field even for a dispersive medium.

The basis for the generation of such a high stream of electrons is the existence of a trapping process taking place in the system. Indeed, when the parallel velocity of the electrons lies in the vicinity of the phase velocity of the ponderomotive propagating potential generated from the nonlinear interaction of the two waves, the electrons might get trapped in this potential and move with it. This trapping is crucial for the onset of the AR acceleration. Moreover, it turns out that under appropriate conditions, it might serve also by itself as a mechanism for generating a high averaged velocity stream of electrons. Whether this stream of electrons will be generated by one mechanism or by the other depends on the choice of the parameters and the initial conditions of the system.

To show this explicitly, we consider the relativistic motion of an electron due to its interaction with a constant uniform magnetic field taken in the z direction and two electromagnetic circularly polarized waves having different frequencies and different wavenumbers counterpropagating along the magnetic field in a dispersive plasma. Using a Hamiltonian formalism, the relativistic equations of motion of an electron could be written as follows:

$$\dot{\psi} = \frac{\partial \bar{H}}{\partial P_\psi} = \frac{1}{Y}\left[-\bar{k}_2\left(\bar{k}_1 P_\phi - \bar{k}_2 P_\psi\right) + 1 + \frac{\bar{A}_1 \sin\phi + \bar{A}_2 \sin\psi}{\sqrt{2\left(P_\phi + P_\psi\right)}} \right] - \bar{\omega}_2 \quad , \qquad (1)$$

$$\dot{\phi} = \frac{\partial \bar{H}}{\partial P_\phi} = \frac{1}{\gamma}\left[+\bar{k}_1\left(\bar{k}_1 P_\phi - \bar{k}_2 P_\psi\right) + 1 + \frac{\bar{A}_1 \sin\phi + \bar{A}_2 \sin\psi}{\sqrt{2\left(P_\phi + P_\psi\right)}} \right] - \bar{\omega}_1 \quad , \qquad (2)$$

$$\dot{P}_\psi = -\frac{\partial \bar{H}}{\partial \psi} = -\frac{\bar{A}_2}{\gamma}\left[\sqrt{2\left(P_\phi + P_\psi\right)} \cos\psi + \bar{A}_1 \sin\left(\phi - \psi\right) \right] , \qquad (3)$$

$$\dot{P}_\phi = -\frac{\partial \bar{H}}{\partial \phi} = -\frac{\bar{A}_1}{\gamma}\left[\sqrt{2\left(P_\phi + P_\psi\right)} \cos\phi - \bar{A}_2 \sin\left(\phi - \psi\right) \right] , \qquad (4)$$

where $$Y = \Big[1 + \left(\bar{k}_1 P_\phi - \bar{k}_2 P_\psi\right)^2 + 2\left(P_\phi + P_\psi\right) + \bar{A}_1^2 + \bar{A}_2^2$$

$$+ 2\sqrt{2\left(P_\phi + P_\psi\right)}\left(\bar{A}_1 \sin\phi + \bar{A}_2 \sin\psi\right) + 2\bar{A}_1\bar{A}_2 \cos\left(\phi - \psi\right) \Big]^{1/2} = \bar{H} + \bar{\omega}_1 P_\phi + \bar{\omega}_2 P_\psi \ . \ (5)$$

These equations have been derived from a conservative Hamiltonian:

$$\bar{H}\left(\psi, \phi, P_\psi, P_\phi\right) = \Big[1 + \bar{A}_1^2 + \bar{A}_2^2 + \left(\bar{k}_1 P_\phi - \bar{k}_2 P_\psi\right)^2 + 2\left(P_\phi + P_\psi\right)$$

$$+ 2\sqrt{2\left(P_\phi + P_\psi\right)}\left(\bar{A}_1 \sin\phi + \bar{A}_2 \sin\psi\right) + 2\bar{A}_1\bar{A}_2 \cos\left(\phi - \psi\right) \Big]^{\frac{1}{2}} - \bar{\omega}_1 P_\phi - \bar{\omega}_2 P_\psi \ . \qquad (6)$$

The wavenumbers are assumed to obey the usual linear dispersion relation associated with electron cyclotron waves, and their normalized expressions take the form :

$$\bar{k}_{1,2} = \sqrt{\left(\bar{\omega}_{1,2}^2 - \frac{e_0 \bar{\omega}_{1,2}}{(\bar{\omega}_{1,2} - 1)} \right)} \quad \text{where} \quad e_0 \equiv \frac{\omega_{pe}^2}{\Omega_{ce}^2} \ . \qquad (7)$$

For details, notations and normalization, we refer the reader to references [1] or [2].

In order to exhibit all these considerations we have solved numerically the set of equations (1) - (4) and presented in ***Fig.I(a)*** a portion of the time dependency of the normalized velocity β_z for a representative electron in the system. As is clearly seen, a particle having initially a relative low parallel velocity $(\beta_{z0} = 0.3324)$ has its velocity increased considerably attaining a time averaged value $\beta_z \cong 0.9$ and retaining this value for a rather long period of time. One readily observes here, the signature of multiple AR processes. Similarly to the case where the index of refraction N is equal to 1 , such an AR process is characterized by a slow variation of one of the phases $(\phi$ or $\psi)$ and the fast variation of the other phase $(\psi$ or $\phi)$ accordingly, thus leading to the averaged in time constancy of the corresponding action.

As for the condition for the system to enter into a AR process, we found it convenient to represent the dynamics of the motion in phase space. The phase space picture β_z versus ξ , (modulo 2π) is shown in ***Fig.I(b).*** ***In*** this figure one sees that just before undertaking an AR acceleration the particle is going through a trapping process. We mention here that the characteristics of such a trapping are : a) the trajectory of the particle is limited to a restricted portion of phase space ; b) the trajectory in phase space is centered around the phase velocity of the ponderomotive well : $\beta_\xi = v_\xi / c = (\bar{\omega}_1 - \bar{\omega}_2)/(\bar{k}_1 + \bar{k}_2)$. These characteristics hold true also for the case $N \neq 1$. The underlying mechanism for the generation of a high averaged parallel velocity retained for a rather long period of time, as presented in ***Fig.I,*** has been the multiple AR process. In this process the trapping condition is an intermediate step for starting an AR interaction which leads to the generation of a high parallel velocity of the particles. As we show now, it turns out that such a trapping in the ponderomotive well might be not an auxiliary step but is itself the basis of a mechanism for generating such a stream of electrons. Indeed, a trapped particle might move together with the ponderomotive propagating well, and its averaged velocity will be large if the parameters of the system are chosen such that β_ξ is large. In ***Fig.II we*** show that such a mechanism is operative. In frame (a), we readily sees a similar behavior of β_z as compared to those represented in ***Fig.I.*** One notices here that the parallel velocity is fluctuating around the phase velocity of the ponderomotive well which is marked by a straight line in the figure. This type of time dependency is definitely of a non AR like characteristic. What is involved here, is really a long trapping process taking place in the system as is apparent upon inspecting ***Fig.II(b).***

In all the examples presented in these figures either characterized by AR processes or by trapping processes, the intermittent nature of the time evolution of the system is always an inherent part of the dynamics which reflects the possibility of the system to undergo a transition to a stochastic state. While, not being a desired feature of the interaction, the real impact of the intermittence of the motion, is very limited when considering a large distribution of particles followed for a long period of time.

In conclusion, we show here that the two waves configuration allows to circumvent the deterioration of the acceleration of the electrons which is characteristic for a dispersive medium. This is achieved by making two mechanisms operational each permitting a rather high parallel velocity built up with a non too large acceleration, utilizing a trapping process of the particles in the ponderomotive well generated from the nonlinear interaction of the two waves. The velocity so acquired might not be enough for accelerators but might be quite sufficient for driving currents.

REFERENCES [1] Y. Gell and R. Nakach, Physics Letters A 207,342 (1995).
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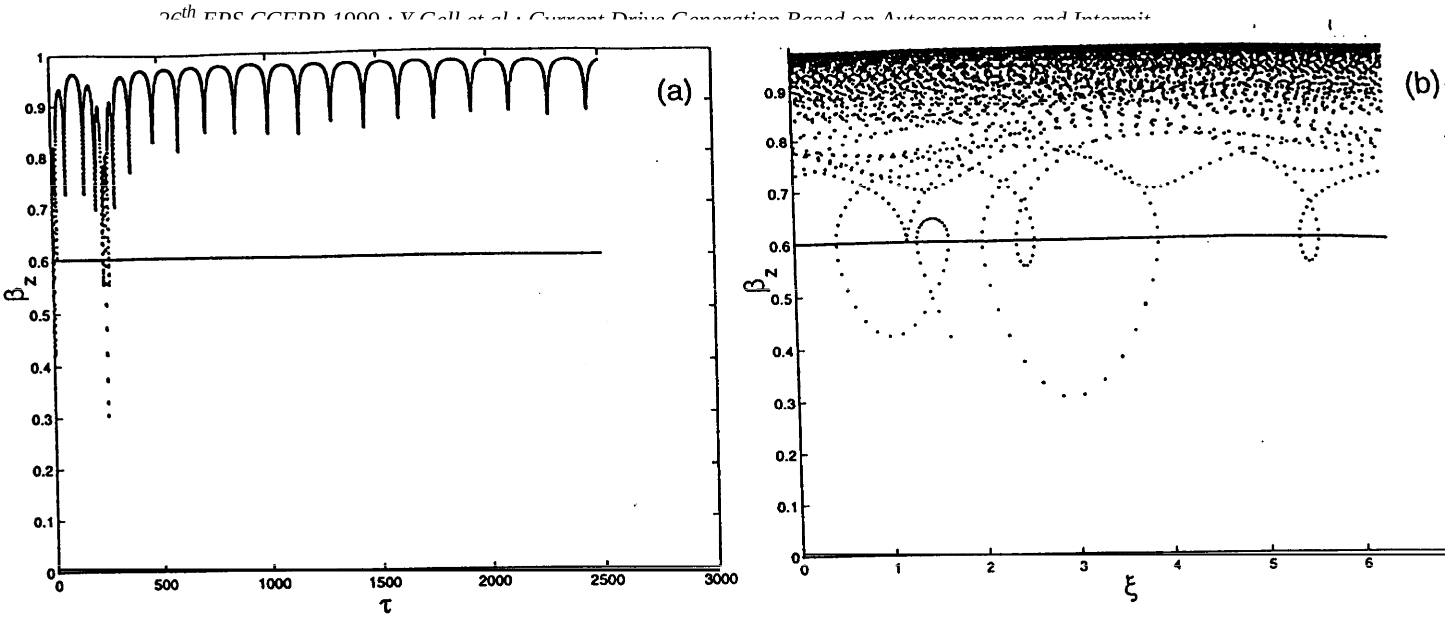

Fig. I (a) The change **with normalized** time τ of the normalized velocity in the z direction, $\beta_z = v_z/c$. The normalized parameters and initial conditions are : $\overline{A}_1=0.45$; $\overline{A}_2=0.06$; $\overline{\omega}_1=3.0$; $\overline{\omega}_2=0.7$; $\phi_0=3.1$; $\psi_0=1.3$; $P_{\phi 0}=0.2$; $P_{\psi 0}=0.08$; $e_0\equiv\frac{\omega_{pe}^2}{\Omega_{ce}^2} = 0.1$. ***The*** waves numbers $(\overline{k}_1,\overline{k}_2)$ were calculated according to ***Eq.(7)*** . ***The*** straight line marks the value of the phase velocity of the ponderomotive well : $\beta_\xi = v_\xi/c = (\overline{\omega}_1-\overline{\omega}_2)/(\overline{k}_1+\overline{k}_2)$. (b) The trajectory of a particle in phase space β_z versus ξ (modulo 2π). The normalized parameters and initial conditions are the same as in Fig. I(a).

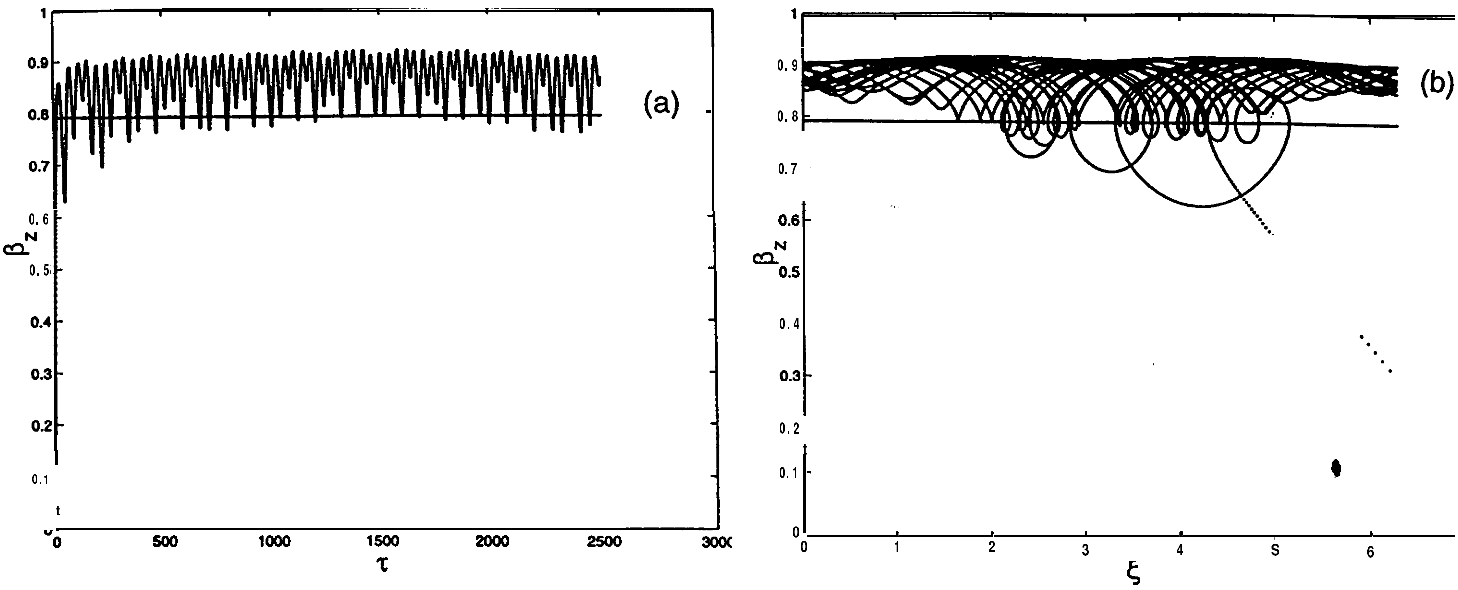

Fig. II (a) The change with normalized time τ of the normalized velocity in the z direction, $\beta_z = v_z/c$. The normalized parameters and initial conditions ***are:*** $\overline{A}_1=0.5$; $\overline{A}_2=0.25$; $\overline{\omega}_1=0.7$; $\overline{\omega}_2=0.03$; $\phi_0=3.1$; $\psi_0=3.1$; $P_{\phi 0}= 0.9$; $P_{\psi 0}= 0.6$; $e_0\equiv\frac{\omega_{pe}^2}{\Omega_{ce}^2} = 0.06$. ***The*** waves numbers $(\overline{k}_1,\overline{k}_2)$ were calculated according to ***Eq.(7)*** . ***The*** straight line marks the value of the phase velocity of the ponderomotive well : $\beta_\xi = v_\xi/c = (\overline{\omega}_1-\overline{\omega}_2)/(\overline{k}_1+\overline{k}_2)$. (b) The trajectory of a particle in phase space β_z versus ξ (**modulo** 2π). The **normalized** parameters and initial conditions are the same as in Fig. II(a).