One-Dimensional Particle-In-Cell Simulation of Electron Acceleration in a Spatially Localized LH Wave

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The interation of electrons with a spatially localized monochromatic lower hybrid wave (LHW) of high amplitude is discussed. Following the resultes in [2] and [5] the Particle-In-Cell (PIC) method (with and without inclusion of the self-consistent field) is used for simulations based on a similar model. The interaction is modeled more realistically by taking in to account relativistic effects. Moreover, we found a strong difference between the interaction of electrons with an LHW of rectangular and one of Gaussian electric-field amplitude profile (assumed to be deeper inside plasma column). Using this simple model, we discuss the effects connected with the anomalous interaction, i.e. the acceleration of electrons with velocities far from the phase velocity, and compare it with the result obtained in [5] from an analytical model. These new results are more realistic nad accurate than the previous ones.

1. Introduction

A lower hybrid wave (LHW) is launched by a grill whose area Γ constitutes only a very small fraction (< 0.01) of the plasma surface S. (E.g., for TORE SUPRA, Γ/S = 0.0022 and for JET, Γ/S = 0.0025). It is usually accepted that an LHW propagates inward the tokamak plasma in an LHW cone. Consequently, the power density in the region actually filled with the RF field much exceeds the power density averaged over the magnetic surface. The dynamics of particles in this RF region can therefore be strongly nonlinear, and the description of the interaction using the quasilinear approximation (based on averaging the RF effect over the magnetic surfaces) can be inadequate. Indeed, we have found [1-5] a strong discrepancy between the numerical simulation with a discrete spectrum of LH waves, and results of the quasilinear description for the equivalent continuous spectrum. Namely, for sufficiently large amplitudes of the RF field, the interaction range in velocity space is substantially larger than the usually considered quasilinear resonant region with $\Delta N_{||}/N_{||} \approx 0.1 - 0.2$.

Our paper is organized as follows. Section 2 describes results obtained by comparing simulations with and without taking into account relativistic effects (without inclusion of the self-consistent field). In Sec. 3, the difference between the interaction of electrons with LHWs of rectangular and Gaussian electric-field amplitude profile is shown. The electron aceleration is discussed especially in terms of the change in the particle-energy fluxes. Section 4 decribes the first result obtained from PIC simulations of electron - LHW interaction with inclusion of self-consictent field, with emphasis on the temporal behaviour and spatial profile of the potential and the self-consistent electric field. Section 5 summarizes the results and discusses the validity of our model as well as its applicability to real experiments.

2. Relativistic effects

In [5] using an exact analytical model, we found strong electron-LHW interaction for electrons passing the LHW region repeatedly. The electrons are accelerated up to velocities close to the velocity of light. Hence, it is neccessary to find the influence of relativistic effects on this interaction.

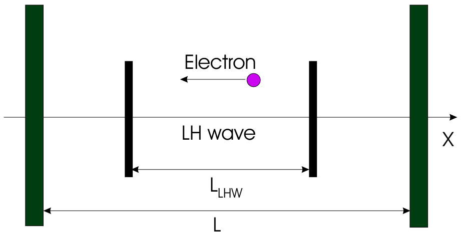

Fig.1: Model arrangement

We consider a situation similar to the one studied in [5], but because of the impossibility of simulating the whole tokamak we take for the simulation volume and the LHW region the lengths L = 0.7 m, which is just a section, and $L_{LHW} = 0.3m$, respectively (Fig. 1). Initially, the electrons are loaded in the simulation volume with a half-Maxwellian distribution and then start moving from right to left. Whenever an electron reaches the left-hand side of the simulation region, it is re-injected from the right-hand side with the same velocity. The few electrons exiting through the right-hand boundary in the early stages of the simulation are removed from the system. Since the present simulations do not take into account the self-consistent interaction between charged particles, ions are not considered explicitly. The LH wave is assumed to have the form of an electrostatic monochromatic wave propagating from right to left, $E = E_0 sin(kx + \omega t)$, with $k > 0, \omega > 0$. We use the following simulation parameters: $E_{0R} = 200kV/m$ (electric-field amplitude of the rectangular profile), $k = 143m^{-1}$ (wave vector), $\omega = 2.32 \times 10^{10} rad/s$ (LH-wave frequency), $n = 5 \times 10^{18} m^{-3}$ (plasma density) and $T = 1keV$ (plasma temperature).

The PIC-simulation results were basically found to agree with the results of our previous exact test-particle model, which uses an analytical formulation of the problem.

Comparisons between non-relativistic and relativistic simulations do not show significant differences regarding the average velocities, but the energy transfer is much enhanced in the relativistic case, resulting in higher absorption of the LH wave. Other quantities monitored, such as the average density and velocity of the electrons, are nearly (i.e., to within a few percent) the same in the non-relativistic and relativistic simulations.

3. Influence of the electric-field amlitude profile of LHW

In this section we compare the interaction of plasma electrons with LHWs characterized by rectangular and Gaussian profiles of the electric-field amplitude. This comparison is motivated by the idea of enhanced absorption of higher spatial harmonics (which are dominant in the rectangular profile) near the plasma edge, which subsequently leads to a change in the spatial profile of the LHW amplitude (initially rectangular) as the wave propagates into the plasma. This effect could significantly influence the plasma-wave interaction deeper inside the plasma column. In the simulations we use the same model as in Sec. 2. The Gaussian profile is taken in the form $E(x) = E_{0G} exp(-8(x - x_c)^2/L^2_{LHW})$, where x_c is the position of the grill center (similar to [6]).

In Figs. 2a) and 2b) we can see that in the case of a Gaussian electric-field amplitude profile ($E_{0G} = 10^3 kV/m$), there is no acceleration even for amplitudes about 5 times higher, as opposed to the strong interaction with the LHW with rectangular amplitude profile.

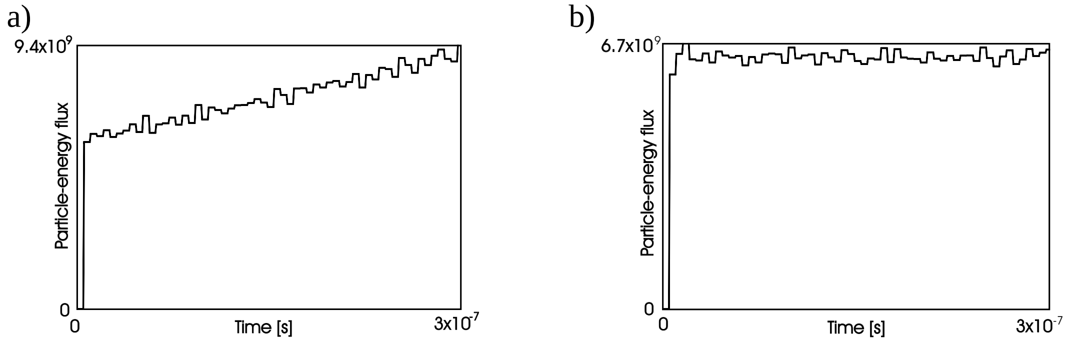

Fig. 2: Particle-energy flux through the left-hand side of the simulation region for a) rectangular and b) Gaussian amplitude profiles.

This is mainly due to the adiabatic change in velocity of the electrons during their motion in an LHW with a Gaussian amplitude profile. By contrast, in the case of rectangular a profile the amplitude changes discontinuously at the bounderes of the LHW region and adiabaticity is not fulfilled, which feature leads to strong electron acceleration.

4. Self-consistant simulation - preliminary results

In order to be closer reality, it is neccessary to take into account the self-consistant interaction between charged particles. We use the same model as in Sec.1. In addition, we take into account the ion component, but in order to suppress the potential fluctuations setting in after some time, we keep the ion background fixed. Initially, the electrons are loaded in the simulation volume with a full Maxwellian distribution. The total simulation time is $t_s = 1,25.10^{-7}s$.

Moreover, in order to suppress the very high potential fluctuation observed, only the first few spatial harmonics of the potential are used for calculating the electron motion.

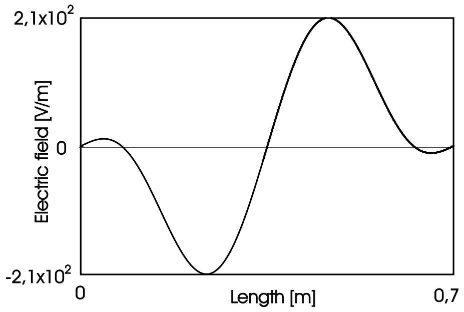

Fig. 3: Time-averaged electric field

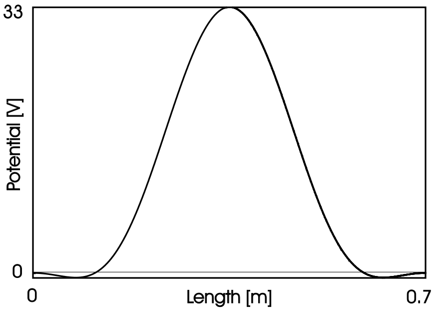

Fig. 4: Time-averaged potential

In Figs. 3 and 4, one can see the time-averaged profiles of the self-consistent eletric field and potential calculated at the final simulation time, which approximately corresponds to 10 electron transits through the simulation region. The electric field and potential are averaged over 10 plasma periods $2\pi/\omega_{pe}$. The electric field equals zero in the center of the simulation region, which also corresponds to the center of the grill. Its maximum and minimum occur near the boundaries of the grill. The maximum value is about 3 orders less than the amplitude of the LH-wave electric field. The potential assumes its maximum in the center of the grill and goes to zero outside. The instantaneous value of the self-consistent electric field oscillates with the plasma frequency ω_{pe} and its maximum is of the order of the amplitude of the LH-wave electric field. The oscillation of the electric field seems to have standing-wave character. As concerns the particle and particle-energy fluxes, the increase is very similar to the case without consideration of the self-consistent field, discussed in detail in Secs. 1 and 2. Also, other quantities (such as temperature, average velocity, distribution function, etc.) are not considerably influenced by taking into account the self-consistent interaction.

5. Summary

In this paper, we have disccussed the electron-LHW interaction by means of PIC simulations, which generalize the results obtained in [5] to be closer to reality.

We have found that the inclusion of relativistic effects does not influence significantly this interaction.

Moreover, we have shown that effects like the broadening of the interaction region in velocity space, the acceleration and deceleration of particles around the phase velocity of the wave, and the resulting change in the distribution function, are strongly connected with the sharply defined rectangular spatial envelope of the LHW field. This is a good approximation close to the grill. Here, the differences from the quasilinear description will be most apparent The step-like spatial profile of the beam is connected with high harmonics of its Fourier representation. A rather fast absorption of higher harmonics in the $k_{||}$-spectrum will lead to a change in the (initially rectangular) spatial shape of the electric-field envelope [4]. This will result in reduced interaction of slower particles with the LH wave. We have shown, that the values of a Gaussian LHW electric-field amplitude require for the stochasticity regime extremely high amplitudes (10^6 V.m^{-1}) and higher.

A preliminary simulation has shown that the self-consistent field does not considerably influence the mechanism of particle acceleration, but we found strong oscillations of this self-consistent field which can have standing-wave character (with frequency equal to the plasma frequency ω_{pe}) and could lead to the generation of Langmuir waves as proposed in [5].

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