Simulation of Collisionless Damping of Shear Alfvén Waves - Applications to Coronal Heating and Solar Wind Acceleration

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We investigate collisionless damping processes of shear Alfvén Waves by using two dimensional, electromagnetic, relativistic Particle-In-Cell (PIC) code. We show the simulation results of two phase-mixing damping processes due to density and magnetic field inhomogeneity, resulting in electron heating. We also investigate the effects of finite amplitude of shear Alfvén waves, longitudinal and transverse modulation that result in strong heating of both electrons and ions. These results are applied to heating of solar corona and acceleration of solar wind.

1. INTRODUCTION

The study of interaction of Alfvén waves (AWs) with plasma inhomogeneities is important for both astrophysical and laboratory plasmas. This is because both AWs and inhomogeneities often coexist in a number of these physical systems. AWs are believed to be good candidates for plasma heating, energy and momentum transport. Heyvaerts and Priest have proposed (in astrophysical context) one such mechanism called AW phase mixing. It occurs when a linearly polarized AW propagates in the plasma with one dimensional, transverse to the uniform magnetic field density inhomogeneity. We study phase mixing effect in the kinetic regime, i.e. we go beyond MHD approximation. We discovered a new mechanism for the acceleration of electrons due to wave-particle interactions. The second example where the phase mixing becomes important is shear AWs propagating in a sheared force-free magnetic field. We found that small amplitude waves end up in strong damping and plasma heating, while AWs of a large enough amplitude can trigger magnetic reconnection in the current sheet. Next we study the transverse and longitudinal modulation of finite amplitude AWs in homogeneous plasmas. We find that both protons and electrons can be strongly heated by the transverse modulation of AWs. These results have important implications for various space and laboratory plasmas, e.g. coronal heating problem and acceleration of solar wind.

2. SIMULATION MODEL AND SIMULATION RESULTS

We used 2D3V, the fully relativistic, electromagnetic, particle-in-cell (PIC) code with MPI parallelisation, modified from 3D3V TRISTAN code. The system size is $L_x = 5000\Delta$ and $L_y = 200\Delta$, where $\Delta = 1.0$ is the grid size. The periodic boundary conditions for $x$ and $y$-directions are imposed on particles and fields. There are about total of 478 million electrons and ions in the simulation. The average number of particles per cell is 100 in low density regions (see below). Thermal velocity of electrons is $v_{th,e} = 0.1c$ and the same for ions is $v_{th,i} = 0.025c$. The ion to electron mass ratio is $m_i/m_e = 16$. The time step is $\omega_{pe}^{-1}$. Here $\omega_{pe}$ is the electron plasma frequency. The Debye length is $\nu_{th,e}/\omega_{pe} = 1.0$. The external uniform magnetic field, $B_0(=1.25)$, is in the $x$-direction and the initialelectric field is zero. Plasma $\beta = 2(\omega_{pe}/\omega_c)^2(v_{th,e}/c)^2 = 0.02$. The dimensionless (normalized to some reference constant value of $n_0 = 100$ particles per cell) ion and electron density inhomogeneity is described by

$$n_i(y) = n_e(y) = 1 + 3\exp\left[-\left(\frac{y-100\Delta}{50\Delta}\right)^6\right] = F(y).$$

(1)

This means that in the central region (across $y$-direction) density is smoothly enhanced by a factor of 4. Then we impose current of the following form

$$\partial_t E_y = -J_0 \sin(\omega_dt) \left(1 - \exp\left[-(t/t_0)^2\right]\right),$$

(2)

$$\partial_t E_z = -J_0 \cos(\omega_dt) \left(1 - \exp\left[-(t/t_0)^2\right]\right).$$

(3)
Here $\omega_d$ is the driving frequency which was fixed at $\omega_d = 0.3\omega_{ci}$, which ensures that no significant ion-cyclotron damping is present. Also, $\partial_t$ denotes time derivative.

The $t_0$ is the onset time of the driver, which was fixed at $50/\omega_{pe}$ or $3.125/\omega_{ci}$. Fig. 1 shows the time development of the AW, resulting in the phase-mixing near the strong density gradient. Our main findings are: Progressive distortion of Alfvén wave front, due to the differences in local Alfvén speed, generates oblique (nearly parallel to the magnetic field) electrostatic fields, which accelerate electrons. The amplitude decay law in the inhomogeneous regions, in the kinetic regime, is shown to be the same as in the MHD approximation described by Heyvaerts & Priest (1983). Due to the present weak non-linearity and plasma inhomogeneity, the density perturbations ($\approx 10\%$) are generated. These are propagating density oscillations with variation both in overall magnitude and across $y$-coordinate. They are mainly confined to the strongest density gradients regions (around $y \approx 50$ and 150). Longitudinal to the external magnetic field, $B_z$, perturbations are also generated in the same manner, but with smaller ($\approx 3\%$) amplitudes. Both in the homogeneous and inhomogeneous cases presence of AWs causes broadening the perpendicular (to the external magnetic field) ion velocities distribution functions, while no ion acceleration is observed. Fig. 2 shows the simulation result of the finite amplitude AWs propagating in force-free magnetic configuration. The AWs penetrate into the current sheet and trigger the magnetic reconnection. The details of the results will be shown in the Conference. Fig. 3 shows the simulation results of the transverse modulation of finite amplitude AW in homogenous plasmas.

3. SUMMARY

We investigated various collisionless damping processes of shear Alfvén Waves by using two dimensional, electromagnetic, relativistic Particle-In-Cell (PIC) code. We showed the simulation results of two phase-mixing damping processes due to density and magnetic field inhomogeneity, resulting in electron heating. We also investigated the effects of finite amplitude of shear Alfvén waves, longitudinal and transverse modulation that result in strong heating of both electrons and ions. These results were applied to heating of solar coronal plasma and acceleration of solar wind.