J. Plasma Physics (2006), *vol.* 72, *part* 6, *pp.* 989–992. © 2006 Cambridge University Press
doi:10.1017/S0022377806005447 Printed in the United Kingdom

Low-frequency instabilities locally enhanced by parallel flow velocity shears in magnetized plasmas

T. KANEKO[1], H. SAITO[1], S. ISHIGURO[2] and R. HATAKEYAMA[1]

[1]Department of Electronic Engineering, Tohoku University, Sendai 980-8579, Japan
[2]National Institute for Fusion Science, Oroshi-cho 322-6, Toki 509-5292, Japan

(Received 22 August 2005 and accepted 1 May 2006)

Abstract. Three-dimensional electrostatic particle simulations are performed in order to investigate the effects of ion flow parallel to magnetic-field lines and their velocity shears on low-frequency plasma instabilities in detail. In the case where the ion drift speed is so small that the low-frequency instabilities cannot take place, the ion-acoustic wave is destabilized by introducing the ion-flow velocity shear. The ion-acoustic wave is locally destabilized in the large velocity shear region. On the other hand, the ion-cyclotron instability is also destabilized when the ion drift speed exceeds a certain threshold. The flow velocity shear enhances not only the fundamental mode but also the high harmonic modes. As a result, the spiky fluctuations in the time domain are locally observed in the velocity shear region, which are caused by the simultaneous existence of several coherent ion-cyclotron harmonics.

1. Introduction

Field-aligned (parallel) plasma flow velocity shears play important roles in the generation of low-frequency plasma instabilities. Recent theoretical works using kinetic treatment have predicted that the parallel flow velocity shear causes electrostatic ion-cyclotron and ion-acoustic instabilities [1]. Experimental results, on the other hand, indicate that the ion-acoustic [2], ion-cyclotron [3], and drift-wave [4] instabilities are excited and suppressed by the parallel velocity shear, where the destabilizing and stabilizing mechanisms are well explained by the kinetic theory. In the experimental investigation, however, it is difficult to change the shape and the location of the velocity shear, and the plasma parameters such as the ratio of the ion to electron temperature, which are very effective in the growth rate of the shear driven instabilities. In this sense, a particle simulation is a very useful method to clarify the effects of the velocity shear, because the simulation can easily set these parameters.

From the viewpoint of investigating the general properties of the velocity shear driven instabilities, the simulation should be performed in the three-dimensional (3D) system because in most cases waves propagate obliquely or perpendicularly to the direction of the flow velocity gradient under the influence of the velocity shear. In this paper, the time evolutions of various spatial Fourier modes of the ion density are investigated using 3D particle simulation [5] in order to understand

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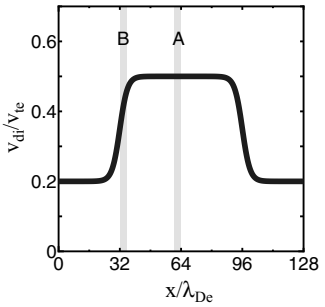


Figure 1. Profile of ion-flow velocity $v_{\rm di}$ in the x direction.

the experimental results and clarify the essential mechanism of the shear driven instabilities.

2. Simulation model

We employ a 3D electrostatic particle simulation with a periodic boundary model, where an external uniform magnetic field directs to the positive z direction. Our simulation code applies the particle-in-cell (PIC) method, which follows particle motions in the self-consistent electric field produced by charged particles. We calculate full ion and electron dynamics. Electrons and ions are uniformly loaded in the system with $L_x \times L_y \times L_z$ at $t = 0$. The system sizes L_x, L_y and L_z are $128\lambda_{\rm De}$, $128\lambda_{\rm De}$ and $512\lambda_{\rm De}$, respectively, and $128 \times 128 \times 512$ spatial grid system is used ($\lambda_{\rm De}$ is the Debye length). The ion to electron mass ratio $m_{\rm i}/m_{\rm e}$ is fixed at 400. The ratio of the electron cyclotron to electron plasma frequency is $\omega_{\rm ce}/\omega_{\rm pe} = 5$, and the ratio of the ion-cyclotron frequency to electron plasma frequency is $\omega_{\rm ci}/\omega_{\rm pe} = 0.0125$. The ion to electron temperature ratio is $T_{\rm i}/T_{\rm e} = 0.5$. The time step width Δt is $0.1\omega_{\rm pe}^{-1}$.

The parallel ion-flow velocity shear is introduced by means of changing the field-aligned ion-flow velocity $v_{\rm di}$ spatially in the x direction as shown in Fig. 1, where $v_{\rm te}$ is electron thermal speed.

3. Simulation results and discussion

Figure 2 shows time evolutions of the real (solid curve) and the imaginary (dashed curve) parts of the spatial Fourier mode of the ion density fluctuation $\tilde{n}_{\rm i}/\bar{n}_{\rm i}$ ($\bar{n}_{\rm i}$ is the time averaged ion density) corresponding to an ion-acoustic wave with $k_y\rho_{\rm i} = 0.54$ and $k_z\rho_{\rm i} = 0.034$, where $\rho_{\rm i}$ is the ion gyroradius, k_y and k_z are wave numbers in y and z directions, respectively. This mode is measured in (a) the uniform ion-flow velocity region ($60 \leqslant x/\lambda_{\rm De} \leqslant 64$) and (b) in the velocity shear region ($32 \leqslant x/\lambda_{\rm De} \leqslant 36$), which are indicated in Fig. 1 as 'A' and 'B', respectively.

The ion-acoustic wave is observed to be destabilized by introducing the ion-flow velocity shear, where the ion drift speed is so small that the low-frequency instabilities cannot occur without the velocity shear. The ion-acoustic wave cannot be observed in the Region A (Fig. 2(a)), while the fluctuation amplitude gradually increases with time in the Region B (Fig. 2(b)). The ion-acoustic wave is found to be locally destabilized in the large velocity shear region.

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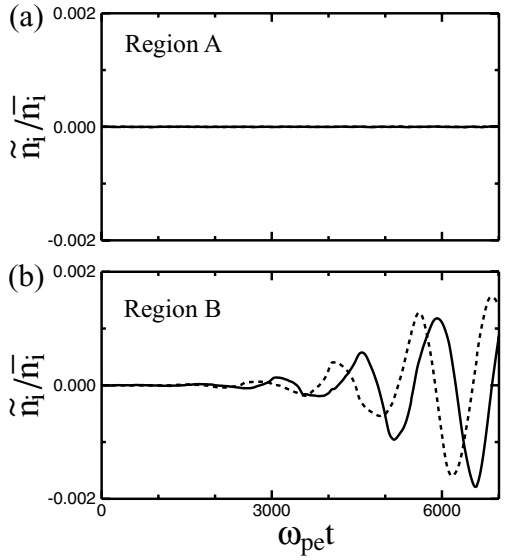


Figure 2. Time evolutions of the real (solid curve) and the imaginary (dashed curve) parts of the spatial Fourier mode of the ion density fluctuation $\tilde{n}_\mathrm{i}/\bar{n}_\mathrm{i}$ for ion-acoustic wave with $k_y\rho_\mathrm{i} = 0.54$ and $k_z\rho_\mathrm{i} = 0.034$ in (a) Region A and (b) Region B.

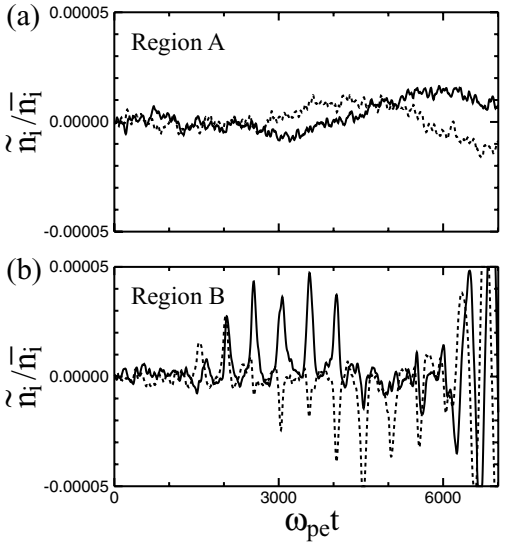


Figure 3. Time evolutions of the real (solid curve) and the imaginary (dashed curve) parts of the spatial Fourier mode of the ion density fluctuation $\tilde{n}_\mathrm{i}/\bar{n}_\mathrm{i}$ for ion-cyclotron wave with $k_y\rho_\mathrm{i} = 0.69$ and $k_z\rho_\mathrm{i} = 0.103$ in (a) Region A and (b) Region B.

Figure 3 presents time evolutions of the real (solid curve) and the imaginary (dashed curve) parts of the spatial Fourier mode of the ion density fluctuation $\tilde{n}_\mathrm{i}/\bar{n}_\mathrm{i}$ corresponding to an ion-cyclotron wave with $k_y\rho_\mathrm{i} = 0.69$ and $k_z\rho_\mathrm{i} = 0.103$ in (a) Region A and (b) Region B. The ion-cyclotron wave is destabilized even in the

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Region A, when the ion drift speed $v_{\rm di}/v_{\rm te}$ exceeds about 0.4, which is the threshold ion-flow velocity to excite the ion-cyclotron wave in the absence of the flow velocity shear in our simulation system. The spiky fluctuations in the time domain are locally observed in the Region B, i.e., in the velocity shear region. These spiky fluctuations result from the simultaneous excitation of several coherent ion-cyclotron harmonics caused by the velocity shear, which is in agreement with the theoretical prediction [1] and experimental results [3]. Based on these results, the flow velocity shear is found to enhance not only the fundamental mode but also the high harmonic modes locally in the large velocity shear region.

4. Conclusions

In order to investigate the effects of parallel ion-flow velocity shear on low-frequency plasma instabilities, we employ a 3D electrostatic particle simulation. The ion-acoustic and ion-cyclotron waves are found to be destabilized by introducing the ion-flow velocity shear. The ion-acoustic wave is locally destabilized in the large velocity shear region, while the wave cannot be observed in the uniform flow velocity region as far as $v_{\rm di}/v_{\rm te} \leqslant 0.5$.

On the other hand, the ion-cyclotron instability is destabilized even in the uniform flow velocity region when the ion drift speed exceeds a certain threshold. The flow velocity shear enhances not only the fundamental mode but also the high harmonic modes. As a result, the spiky fluctuations in the time domain are locally observed in the velocity shear region, which are caused by the simultaneous existence of several coherent ion-cyclotron harmonics. These results are qualitatively consistent with the analysis based on the local theory which shows that the growth rate of the instabilities depends on the localized shear strength and predicts the simultaneous excitation of the ion-cyclotron harmonics [1].

Acknowledgements

This work was performed with the support and under the auspices of the National Institute for Fusion Science (NIFS) Collaborative Research Program. The computation were performed by the Plasma Simulator at NIFS.

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