Nonlinear Evolution of Lower-Hybrid Drift Instability in Harris Current Sheet *

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We perform 2.5-dimensional particle-in-cell simulations to investigate the nonlinear evolution of the lower hybrid drift instability (LHDI) in Harris current sheet. Due to the drift motion of electrons in the electric field of the excited low hybrid drift (LHD) waves, the electrons accumulate at the outer layer, and therefore there is net positive charge at the inner edge of the current sheet. This redistribution of charge can create an electrostatic field along the z direction, which then modifies the motions of the electrons along the y direction by $\boldsymbol{E}\times\boldsymbol{B}$ drift. This effect strongly changes the structure of the current sheet.

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Current sheets that separate oppositely directed magnetic field lines are usually observed in solar, planetary and laboratory plasma environments. Their disruption or filamentation can lead to magnetic reconnection. Magnetic reconnection is considered as the most important mechanism, which converts magnetic energy into plasma kinetic energy.[1,2] One prominent example to this process is substorm in Earth's magnetosphere.[3,4] The geospace environment magnetic (GEM) reconnection challenge (see Ref. [5] and references therein) has clarified the importance of Hall current term in the physics of fast magnetic reconnection. However, the onset of reconnection, i.e. how the current sheet evolves into reconnection stage is still not clear. On the other hand, the current sheet with a thickness on the order of ion scale is unstable to a variety of instabilities. These instabilities may be important in the evolution of current sheet and therefore are considered to be closely related to the onset problem of reconnection. One of the most extensively studied instabilities is lower-hybrid drift instability (LHDI), which is driven by the diamagnetic current in the presence of inhomogeneities of the density and magnetic field.[6] According to the linear theory, the fastest growing modes are primarily electrostatic with $\boldsymbol{k}\cdot\boldsymbol{B}=0$ (where $\boldsymbol{k}$ is the wave number, and $\boldsymbol{B}$ is the background magnetic field), and the wavelength is on the electron scale. The previous theories considered the LHDI as a possible source of anomalous resistivity required in classic reconnection model. Unfortunately, the linear theory predicts that the fastest growing mode is localized at the edge of the current sheet due to the finite beta effect.[7] Therefore, it is impossible for the linear LHDI to provide any significant anomalous resistivity in the current sheet. The linear LHDI at the edge of the current sheet has been observed in magnetosphere[8,9] and laboratory plasma.[10]

Recently, Daughton[11] found that in a thin current sheet the longer wavelength modes have a significant electromagnetic component, which can penetrate into the central region of the current sheet during their nonlinear evolutions. Actually, besides providing anomalous resistivity, the LHDI can also influence the thin current sheet in other ways. First, the LHDI can strongly modify the structure of the current sheet, make the current sheet peaked and bifurcated in its central region.[12] Second, it causes anisotropic heating of electrons, preferentially in the perpendicular direction.[13,14] These effects of electron dynamics will efficiently enhance the growth rate of collisionless tearing mode,[15] therefore may play an important role in the onset of magnetic reconnection. In this Letter, we investigate the nonlinear evolution of the LHDI in Harris current sheet with 2.5-dimensional (2.5-D) particle-in-cell simulations. Different from Daughton *et al.*[12] who proposed that the structure of the current sheet is modified by the interactions between the LHD waves and magnetized ions, we find that the drift motion of electrons in the electric field of the excited LHD waves makes electrons accumulate at the outer layer, and therefore there will be net positive charge at the inner edge of the current sheet. This leads to an electrostatic field along the z direction in the current sheet. Its significance on the modification of the structure of the current sheet is also discussed.

In particle-in-cell simulations, the electromagnetic fields are defined on the grids. Both the ions and

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electrons are advanced self-consistently in the electromagnetic fields. In our 2.5-D simulation code,[16] the electromagnetic fields are updated by solving the Maxwell equations with a full explicit algorithm, and the simulations are performed in the y–z plane. One-dimensional (1-D) Harris current sheet is considered in initial configurations, which is given by

$$\boldsymbol{B}_0(z) = B_0 \tanh(z/L)\boldsymbol{e}_x, \quad (1)$$

where B_0 is the asymptotic magnetic field and L is the half-width of current sheet. The plasma number density is given by

$$n_0(z) = n_0 \mathrm{sech}^2(z/L), \quad (2)$$

where n_0 is initial plasma number density in the centre of current sheet. The thickness of the current sheet thickness is set to be $L = 0.7c/\omega_{pi}$, where c/ω_{pi} is the ion inertial length defined by the peak Harris density n_0. In the simulations we employ about 3×10^6 particles to represent the ion/electron component. The initial velocity distributions of the ions and electrons are Maxwellian, and their drift speeds in the y direction satisfy $v_{i0}/v_{e0} = -T_{i0}/T_{e0}$, in which the temperature ratio of the ion to electron is chosen as $T_{i0}/T_{e0} = 5$ (where the subscripts i and e stand for the ion and electron, respectively). The diamagnetic current is $J_0(z) = en_0(z)(v_{i0} - v_{e0})$. The mass ratio is taken to be $m_i/m_e = 180$ and the light speed in vacuum is set to be $c = 15v_A$, where v_A is the Alfven speed defined based on B_0 and n_0. The dimension of the simulation box is $L_x \times L_y = (12.8c/\omega_{pi}) \times (6.4c/\omega_{pi})$, where L_x and L_y are the spatial length in the x and y directions, respectively. The time step is $\Omega_{ci}\Delta t = 0.001$, in which Ω_{ci} is ion gyro-frequency defined by B_0, and the grid size is $\Delta y \Delta z = 0.025c/\omega_{pi}$. Periodic boundary conditions are used in the y direction. The ideal conducting boundary conditions for electromagnetic fields are employed in the z direction, and particles are reflected if they reach the boundaries.

Different from the work in GEM reconnection challenge,[5] no initial perturbation is imposed to study the early phase of the LHDI in the Harris current sheet. Figures 1(a), 1(b) and 1(c) show the x-component of magnetic fluctuations $(B_x - B_0 \tanh(z/L))/B_0$, in which the initial magnetic field has been subtracted to show the variation of magnetic field, the y-component of electric field $(c/v_A)(E_y/B_0)$, and the electron density of electrons n_e/n_0 at $\Omega_{ci}t = 2.0$, which is in the early phase of the LHDI. It is found that in the initial phase the fluctuations of both the magnetic field and electric field are well confined at the edge region and propagate along the y direction, and there are no significant fluctuations in the central region of the current sheet. The fluctuations of the electron density are also confined in the centre of the current sheet. These results are consistent with the linear theory.[7] In the nonlinear stage of the LHDI, the fluctuations corresponding to the LHDI move to the centre of the current sheet. Figures 2(a), 2(b) and 2(c) show the x-component of magnetic fluctuations $(B_x - B_0 \tanh(z/L))/B_0$, the y-component of electric field $(c/v_A)(E_y/B_0)$, and the electron density of electrons n_e/n_0 at $\Omega_{ci}t = 4.4$, which is in the nonlinear stage. We can find that the fluctuations of the magnetic field begin to emerge in the centre of the current sheet, and the amplitude can be as large as $\Delta B/B_0 \approx 0.4$. In contrast to the magnetic fluctuations, the electric field fluctuations are still confined at the edge of the current sheet. However, the modes with larger wavelength are now excited and their amplitude is enhanced. The electron density is strongly modified by nonlinear effect of the LHDI and thus the width of the current sheet considerably thinned.

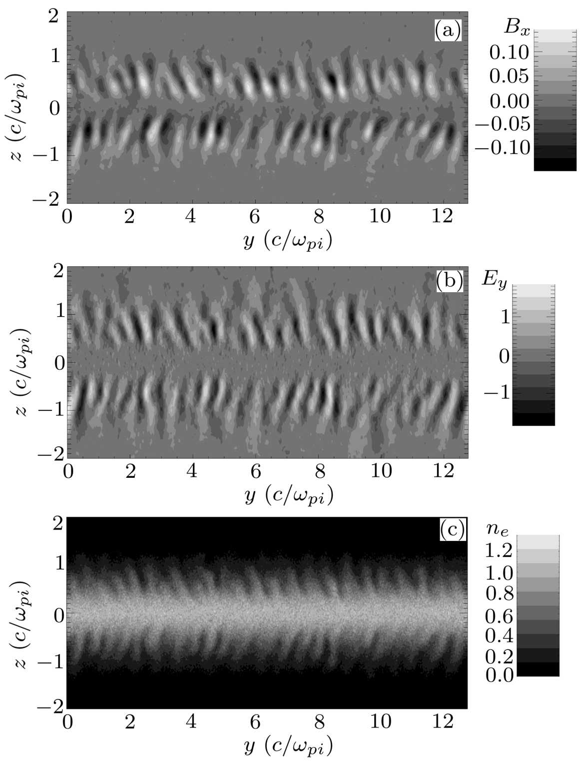

Fig. 1. (a) The x-component magnetic fluctuations $(B_x - B_0\tanh(z/L))/B_0$ of, in which the initial magnetic field has been subtracted to show the variation of magnetic field, (b) the y-component electric field $(c/v_A)(E_y/B_0)$, and (c) the electron density of electrons n_e/n_0 at $\Omega_{ci}t = 2.0$. Here magnetic field, electric field and electron density are the dimensionless parameters.

An interesting issue is the motions of the electrons and how they modify the current density. Figures 3(a) and 3(c) show the z-component of average electron velocity V_{ez}/v_A and the charge density represented by the difference between ion density and electron density $(n_i - n_e)/n_0$ at $\Omega_{ci}t = 2.8$. It is found that the average electron velocity V_{ez}/v_A is governed by $\boldsymbol{E} \times \boldsymbol{B}$ drift caused by the electric field E_y of the excited waves. Since ions are largely unmagnetized, the electric field has a relative weak influence on the ions and therefore will create the separate motion between ions and electrons. The ion density will be higher than electron density where the electrons move outwards, while the electron density will be higher than that of ions where the electrons move inwards. Because of the initial density gradient, the total electron density will decrease in the inner side and increase in the outer side.

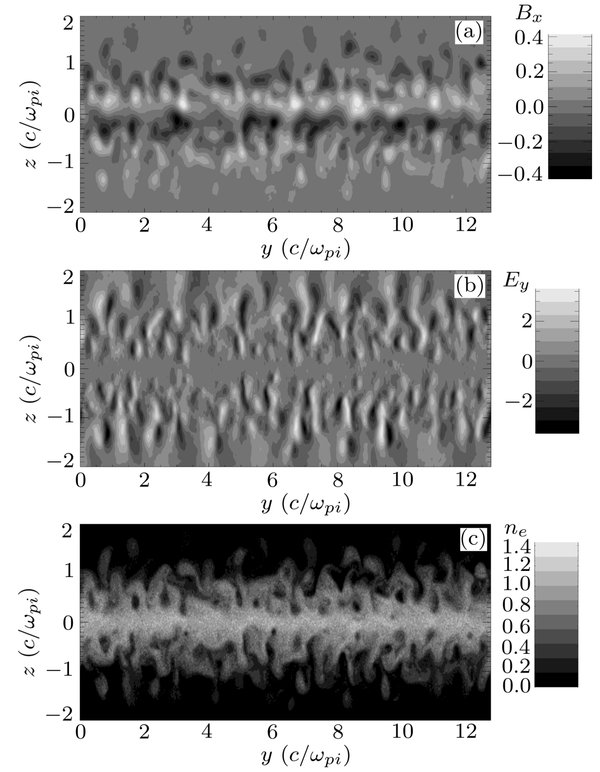

Fig. 2. (a) The x-component magnetic fluctuations $(B_x - B_0 \tanh(z/L))/B_0$, (b) the y-component electric field $(c/v_A)(E_y/B_0)$, and (c) the electron density of electrons n_e/n_0 at $\Omega_{ci}t = 4.4$.

Due to the existing initial density inhomogeneity, the total electron density will decrease in the inner side and increase in the outer side. This can be found in Fig. 4, which describes $\langle n_i - n_e \rangle/n_0$ at $\Omega_{ci}t = 2.8$, and has been averaged over the y direction. The maximum value of the positive charge is 0.02 at $z = 0.04$, and the maximum value of negative charge is -0.01 at $z = 0.08$. This is in good agreement with the wave activity region of excited waves. Note that there is a weak loss of positive charges in the central region of current sheet, which is consistent with the results reported by Daughton *et al.*[12] who attributed this to the interactions between the LHD waves and magnetized ions. Their results show that the excited waves will scatter the crossing ions into the noncrossing region in phase space, which give rise to the accumulation of ions on the edge and thus form an electrostatic potential structure across the current sheet. However, it is too weak to interpret the accumulation of the positive charge at the edge of the current sheet.

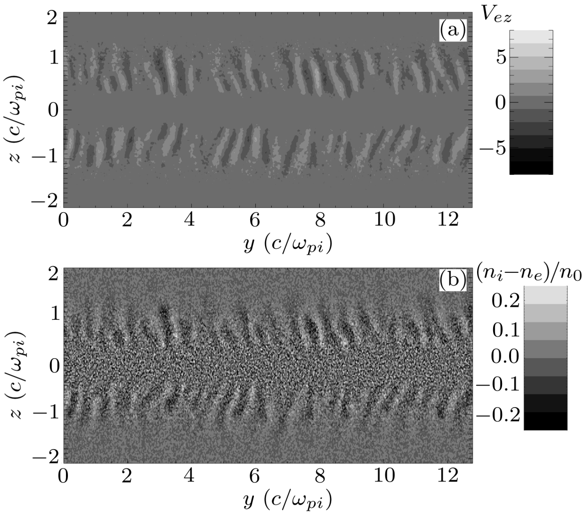

Fig. 3. (a) The z-component average electron velocity V_{ez}/v_A, (b) the charge density represented by the difference between ion density and electron density $(n_i - n_e)/n_0$ at $\Omega_{ci}t = 2.8$.

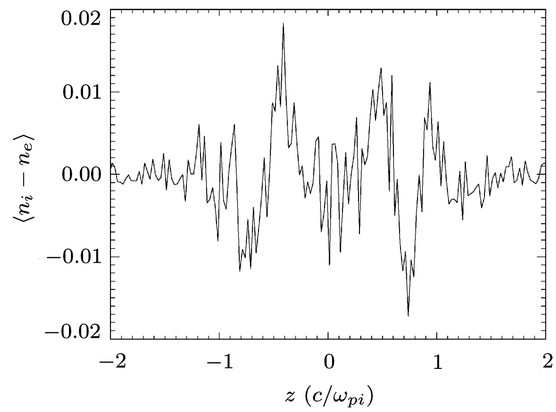

Fig. 4. Distribution of $\langle n_i - n_e \rangle/n_0$ at $\Omega_{ci}t = 2.8$, which has been averaged over the direction of y.

In summary, we have investigated the nonlinear evolution of the LHDI in Harris current sheet. The simulation domain is in current sheet plane. It does not allow reconnection to occur, and can only examine the effect of LHDI in the evolution of current sheet. The simulations show that the dynamics of electrons governs the nonlinear evolution of the current sheet, at least during the nonlinear stage (several ion cyclotron periods) we considered in this study. The dynamics of electrons are controlled by the $\boldsymbol{E} \times \boldsymbol{B}$ drift motion in the electric field of excited LHD waves. There will be net positive charges at the inner layer and negative charges at the outer layer of current sheet. This process will in turn create an electrostatic potential structure which enables the acceleration of electrons. The different motion between electrons and ions may play an important role in the onset of current sheet. In order to fully reveal the issue of the onset of reconnection, three-dimensional simulations with high ion to electron mass ratio should be implemented. However, the required high spatial and temporal resolution is beyond current available computation.

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