Ion and electron heating during magnetic reconnection in weakly collisional plasmas

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Introduction

Magnetic reconnection is a commonly observed fundamental process in both astrophysical and fusion plasmas. It allows topological change of magnetic field lines, and converts the free energy in the magnetic field into various forms of energy, such as bulk plasma flows, plasma heating, or non-thermal particle acceleration. In this paper, we consider ion and electron (irreversible) heating during magnetic reconnection in weakly collisional plasmas.

In weakly collisional plasmas, phase mixing processes caused by kinetic effects, such as Landau damping and finite Larmor radius (FLR) effects, create oscillatory structures in velocity space, which must eventually be regularized by collisions. Therefore, even if collisions are infrequent, energy dissipation and resulting plasma heating may be significant, as demonstrated by recent investigations using both a reduced [1] and a fully gyrokinetic model [2]. The study of plasma heating due to phase mixing has also been extended for high beta plasmas [3], where ion heating is also expected to be significant since compressible fluctuations will be excited which are strongly damped collisionlessly.

We perform a detailed analysis of ion and electron heating during magnetic reconnection by means of gyrokinetic simulations for high beta plasmas, and discuss the importance of ion and electron heating due to phase mixing. For high beta plasmas, ion heating is shown to be comparable with electron heating. Perpendicular phase mixing structures due to FLR effects develop as well as those of parallel phase mixing for ions.

Problem setup

We consider magnetic reconnection of strongly magnetized plasmas in a two-dimensional doubly periodic slab domain. We initialize the system by a tearing unstable magnetic field configuration (see [4, 5] for details). The equilibrium magnetic field profile is

$$\boldsymbol{B} = B_{z0}\hat{z} + B_y^{\mathrm{eq}}(x)\hat{y}, \quad B_{z0} \gg B_y^{\mathrm{eq}}, \tag{1}$$

where B_{z0} is the background guide magnetic field and $B_y^{\rm eq}$ is the in-plane, reconnecting component, related to the parallel vector potential by $B_y^{\rm eq}(x) = \partial A_\parallel^{\rm eq}/\partial x$, and

$$A_\parallel^{\rm eq}(x) = A_{\parallel 0}^{\rm eq} \cosh^{-2}\left(\frac{x - L_x/2}{a}\right) S_{\rm h}(x). \tag{2}$$

($S_{\rm h}(x)$ is a shape function to enforce periodicity.) $A_\parallel^{\rm eq}$ is generated by the electron parallel current to satisfy the parallel Ampère's law. The equilibrium scale length is denoted by a and L_x is the length of the simulation box in the x direction, set to $L_x/a = 3.2\pi$. In the y direction, the box size is $L_y/a = 2.5\pi$. We impose a small sinusoidal perturbation to the equilibrium magnetic field, $\tilde{A}_\parallel \propto \cos(k_y y)$ with wave number $k_y a = 2\pi a/L_y = 0.8$, yielding a value of the tearing instability parameter $\Delta' a \approx 23.2$.

The equilibrium magnetic field defines the time scale of the system. We normalize time by the Alfvén time $\tau_{\rm A} \equiv a/V_{\rm A}$ where $V_{\rm A} \equiv B_y^{\rm max}/\sqrt{\mu_0 n_0 m_{\rm i}}$ is the Alfvén velocity corresponding to the peak value of $B_y^{\rm eq}$, n_0 is the background plasma density of ions and electrons, and μ_0 is the vacuum permeability.

We solve fully electromagnetic gyrokinetic equations for electrons and ions using `AstroGK`. The code employs a pseudo-spectral algorithm for the spatial coordinate (x, y), and Gaussian quadrature for velocity space integrals. The velocity space is discretized in the energy $E_s = m_s v^2/2$ (m_s is the mass and $s = {\rm i}, {\rm e}$ is the species label) and $\lambda = v_\perp^2/(B_{z0} v^2)$. The velocity space grids are set to $N_\lambda = N_E = 64$, and the spatial resolution in the x, y directions are $N_x = 512$, $N_y = 128$ subject to the 2/3 rule for dealiasing. The number is determined by the convergence test [3].

Parameters in the system are chosen as follows: The mass ratio, $\sigma \equiv m_{\rm e}/m_{\rm i} = 0.01$, the temperature ratio of the background plasma, $\tau \equiv T_{0{\rm i}}/T_{0{\rm e}} = 1$, the electron plasma beta, $\beta_{\rm e} \equiv n_0 T_{0{\rm e}}/(B_{z0}^2/2\mu_0) = 1$, and the ratio of the ion sound Larmor radius to the equilibrium scale length a, $\rho_{\rm Se}/a \equiv c_{\rm Se}/(\Omega_{\rm ci} a) = 0.25/\sqrt{2}$. The ion sound speed is $c_{\rm Se} = \sqrt{T_{0{\rm e}}/m_{\rm i}}$, and the ion cyclotron frequency is $\Omega_{\rm ci} = eB_{z0}/m_{\rm i}$. The physical scales associated with the non-magnetohydrodynamic (MHD) effects are $\rho_{\rm i} = d_{\rm i} = 10\rho_{\rm e} = 10 d_{\rm e} = 0.25$.

Simulation results

We perform nonlinear simulations in the collisionless tearing-mode regime where the frozen-flux condition is not broken by collisions. To estimate plasma heating, we measure the collisional energy dissipation rate,

$$D_s = -\int\!\!\int \left\langle \frac{T_{0s} h_s}{f_{0s}} \left(\frac{\partial h_s}{\partial t}\right)_{\rm coll} \right\rangle_{\boldsymbol{r}} {\rm d}\boldsymbol{r}{\rm d}\boldsymbol{v} \geq 0. \tag{3}$$

Without collisions, the gyrokinetic equation conserves the generalized energy consisting of the particle part E_s^{p} and the magnetic field part $E_{\perp,\parallel}^{\mathrm{m}}$

$$W = \sum_s E_s^{\mathrm{p}} + E_\perp^{\mathrm{m}} + E_\parallel^{\mathrm{m}} = \int \left[\sum_s \int \frac{T_{0s}\delta f_s^2}{2 f_{0s}} \mathrm{d}\boldsymbol{v} + \frac{\left|\nabla_\perp A_\parallel\right|^2}{2\mu_0} + \frac{\left|\delta B_\parallel\right|^2}{2\mu_0} \right] \mathrm{d}\boldsymbol{r} \quad (4)$$

where $\delta f_s = -q_s\phi/T_{0s} f_{0s} + h_s$ is the perturbation of the distribution function, h_s is the non-Boltzmann part obeying the gyrokinetic equation, and the generalized energy is dissipated by collisions as $\mathrm{d}W/\mathrm{d}t = -\sum_s D_s$. The collisional dissipation increases the entropy (related to the first term of the generalized energy), and is turned into heat [6].

Figure 1 shows time evolutions of the reconnection rate measured by the electric field at the X point $(x,y) = (L_x/2, L_y/2)$, and the collisional energy dissipation rate. The peak reconnection rate is fast (~ 0.1). The electric field suddenly drops after the maximum reconnection rate because the secondary island is formed, and is no more a measure of the reconnection rate. The dissipation rates of electrons and ions grow slower than the time scale of reconnection. The electron dissipation rate peaks shortly after the peak reconnection rate, and the ion dissipation rate takes much longer time to achieve its maximum value. The dissipated energy is about 10% (40%) of the released magnetic energy at the peak of electron (ion) dissipation rate $t/\tau_{\mathrm{A}} = 43$ ($t/\tau_{\mathrm{A}} = 50$).

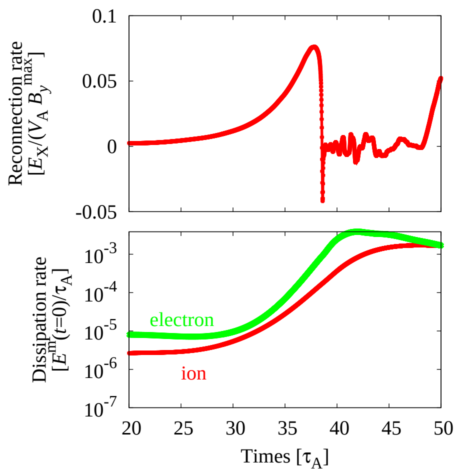

Figure 1: Time evolutions of the reconnection rate, and the dissipation rate of ions and electrons.

To illustrate how the energy is dissipated from the system, we plot, in Fig. 2, spatial distributions of the dissipation rates together with the isolines of $A_\parallel$, and the distribution functions taken where the dissipation is large. The electron dissipation at $t/\tau_{\mathrm{A}} = 37.8$ mostly occurs along the separatrix. The electron distribution function taken where the dissipation rate is large only has gradients in the $v_\parallel$ direction indicating parallel phase mixing, and the scale length becomes smaller as time progresses (not shown). It is shown by spatial distribution of the ion dissipation at the later time ($t/\tau_{\mathrm{A}} = 46.9$) that the ion dissipation is mostly confined in the secondary island stayed at the center of the domain. The ion distribution function develops structures in the $v_\perp$ direction, as well as the parallel direction, manifesting the perpendicular FLR phase mixing. Since the FLR phase mixing is nonlinear, it is significant only when nonlinear effects are well developed.

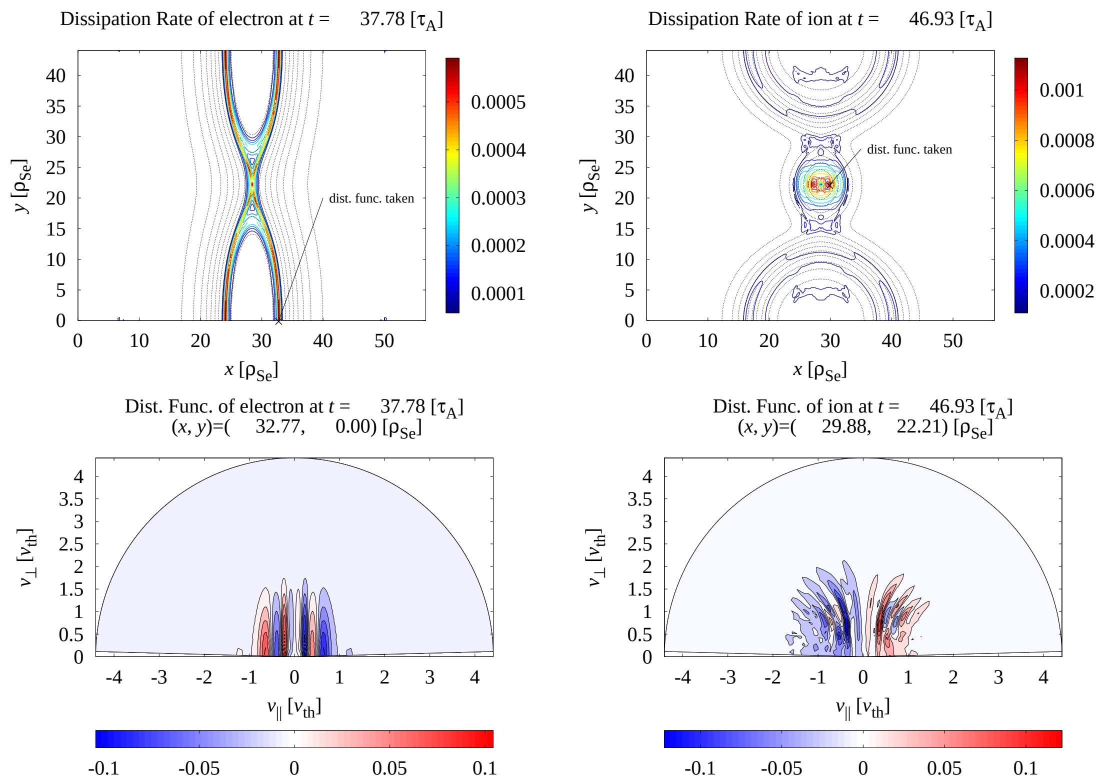

Figure 2: Spatial distribution of the dissipation rate of electrons at $t/\tau_{\rm A} = 37.8$ (top left) and that of ions at $t/\tau_{\rm A} = 46.9$ (top right). The distribution functions of electrons and ions taken where the dissipation rate is large are shown in bottom panels.

Conclusion

We have performed gyrokinetic simulations to investigate plasma heating during magnetic reconnection in weakly collisional plasmas. We have shown that an appreciable fraction of the released magnetic energy is dissipated from the system due to phase mixing to heat the background plasmas. For high beta plasmas, electron heating is caused by linear parallel phase mixing, while ion heating is caused both by linear parallel and nonlinear perpendicular phase mixing. The dissipation rates of ions and electrons are comparable for high beta plasmas.

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