Energy partition in kinetic turbulent reconnection

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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 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 can be significant. This heating mechanism due to phase mixing has been demonstrated using both a reduced [1] and a fully gyrokinetic model [2]. It has also been found that, for high beta gyrokinetic plasmas, the current sheet becomes unstable, and the resultant plasmoid (secondary island) can significantly alter the efficiency of electron and ion heating. This finding suggests that more efficient energy conversion may take place in turbulent reconnection, which is likely to be present in natural environment.

In this paper, we present a preliminary study of plasma heating in turbulent magnetic reconnection in strongly magnetized plasmas.

Ion and electron heating via phase mixing

In this section, we summarize the previous result of ion and electron heating due to phase mixing during magnetic reconnection by means of gyrokinetic simulations. (Full details are described in [2].)

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. The equilibrium magnetic field profile is $\boldsymbol{B} = B_{z0}\hat{z} + B_y^{\mathrm{eq}}(x)\hat{y}$ ($B_{z0} \gg B_y^{\mathrm{eq}}$), where B_{z0} is the background guide magnetic field and B_y^{eq} is the in-plane, reconnecting component, related to the parallel vector potential by $B_y^{\mathrm{eq}}(x) = \partial A_{\parallel}^{\mathrm{eq}}/\partial x$, and $A_{\parallel}^{\mathrm{eq}}(x) \propto A_{\parallel 0}^{\mathrm{eq}} \cosh^{-2}(x/a)$ ($A_{\parallel 0}^{\mathrm{eq}}$ is a constant and a is the magnetic shear length). The maximum of B_y^{eq} is used to define the Alfvén time τ_{A}, which characterizes the time scale of the system. We impose a sinusoidal perturbation to initiate magnetic reconnection. Simulations are performed in the collisionless tearing-mode regime where the frozen-flux condition is not broken by collisions.

During magnetic reconnection process, the initial magnetic energy is redistributed. To estimate plasma heating, we measure the collisional energy dissipation rate of species s, D_s. Without collisions, the gyrokinetic equation conserves the generalized energy W, and it is dissipated by collisions as $\mathrm{d}W/\mathrm{d}t = -\sum_s D_s$. The collisional dissipation increases the entropy, and is turned into heat [3].

Figure 1, left column shows the temporal evolution of the reconnection rate (top), energy components (middle), and dissipation rate (bottom) for a high-beta case ($\beta_{\mathrm{e}} = 1$). Looking at the reconnection rate measured by the electric field at the center of the domain (E_X), we observe that magnetic reconnection occurs around $t/\tau_{\mathrm{A}} = 30 \sim 40$, followed by a plasmoid formation ($t/\tau_{\mathrm{A}} = 40$) and ejection ($t/\tau_{\mathrm{A}} = 50$). (Note that, after the plasmoid formation, E_X is not a proper measure of the reconnection rate since the center of the domain becomes an O point.)

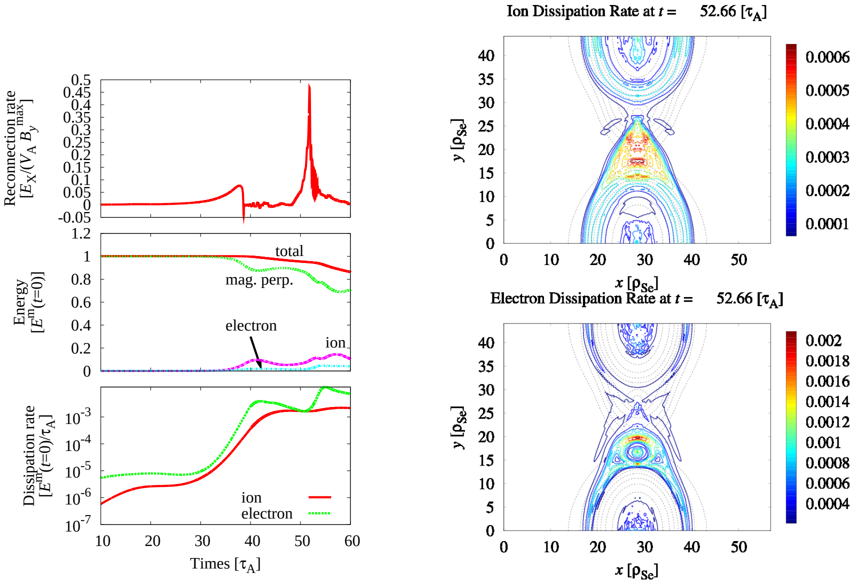

Figure 1: Left: Temporal evolution of reconnection rate, energy components, and dissipation rate. Right: spatial distribution of dissipation rate of ions and electrons at the plasmoid ejection. Length is normalized by the ion sound Larmor radius $\rho_{\mathrm{Se}} = 0.177a$.

In the initial reconnection phase ($t/\tau_{\mathrm{A}} = 30 \sim 40$), the energy dissipation rate gradually increases, and an appreciable amount of energy is converted into ion and electron heating. To detail the heating process, we plot the spatial distribution of the dissipation rate in Fig. 1, right column. The plots show the dissipation rate of ions and electrons at the plasmoid ejection phase. If we look at the distribution function at the place where strong dissipation is occurring, we see clear phase mixing structure in velocity space [2]. We also found that the energy dissipation of electrons are significantly enhanced at the newly formed X point when a plasmoid is formed [2].

Driven simulation

To study efficient energy conversion by turbulence during magnetic reconnection, we drive turbulence in the system. We have implemented and tested two types of driving forces:

- Oscillating Langevin Antenna [4]

  The oscillating Langevin antenna is already implemented in `AstroGK`, which drives a current in the z direction (perpendicular to the reconnection plane). It consists of the driven/damped oscillator and white noise:

  $$\frac{\mathrm{d}A_{\parallel,\boldsymbol{k}_{\mathrm{a}}}}{\mathrm{d}t} = -\mathrm{i}\omega_{\mathrm{a}} A_{\parallel,\boldsymbol{k}_{\mathrm{a}}} + F_{\mathrm{a}}, \tag{1}$$

  where ω_{a} is a complex frequency, F_{a} is a random number, and $\boldsymbol{k}_{\mathrm{a}}$ is the wave number of the mode that we wish to drive.

- Direct forcing

  We can also add direct driving force in the gyrokinetic equation evolving the non-Boltzmann part of the distribution function h_s,

  $$\frac{\partial h_s}{\partial t} = \cdots + F f_{0s}, \tag{2}$$

  where F is a random noise, and is independent of velocity, f_{0s} is the Maxwellian distribution function. This forcing induces perturbations of density and electrostatic potential, thus results in driving perpendicular flows due to the $\boldsymbol{E} \times \boldsymbol{B}$ drift.

Figure 2, top panel shows the reconnection for the cases with i) the antenna drive with $\omega_{\mathrm{a}}\tau_A = 800$, $\boldsymbol{k}_{\mathrm{a}}\rho_{\mathrm{Se}} = (2.5/\sqrt{2}, 1.6/\sqrt{2})$ for $\beta_{\mathrm{e}} = 1, 0.01$, and ii) direct forcing for $\beta_{\mathrm{e}} = 0.01$. By the antenna with $\omega_{\mathrm{a}}\tau_A = 800$, a thin current layer is supported for long time, and higher reconnection rate is achieved. However, the current sheet structure shown in Fig. 2, bottom-left panel, is rather laminar, and turbulence seems not to be excited. The direct forcing, on the other hand, can efficiently drive turbulence as shown in Fig. 2, bottom-right panel.

Conclusion

Magnetic reconnection can efficiently convert energy to heat via phase mixing in strongly magnetized plasmas, as has been proved by gyrokinetic simulations. In this study, we have considered two different methods to drive turbulence in gyrokinetic magnetic reconnection simulation to investigate effects of turbulence on plasma heating. It seems the direct drive is advantageous because i) it can effectively drive turbulence in two-dimensional case, ii) it is directly

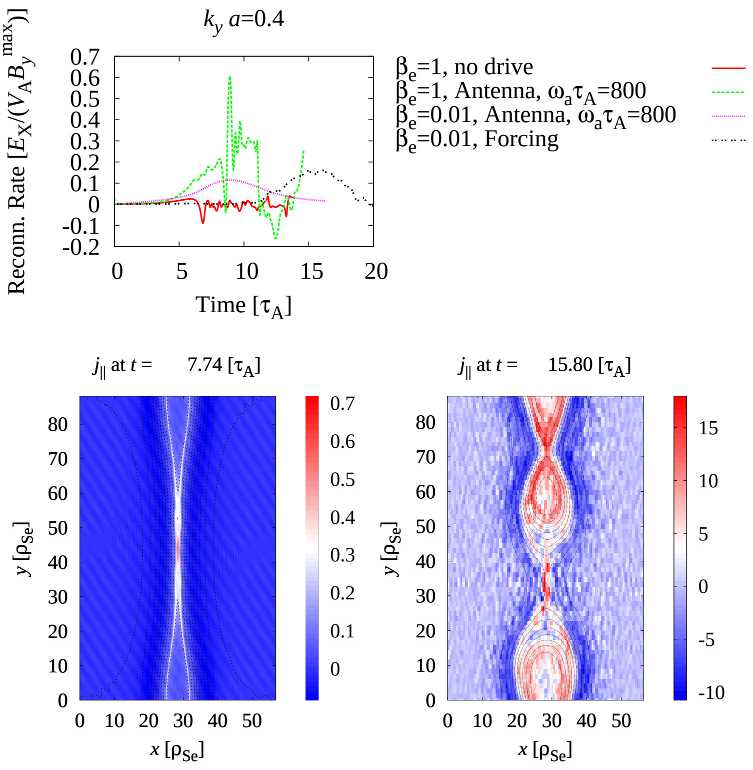

Figure 2: Top: Reconnection rate for the cases with various driving forces. Bottom: Current distribution for $\beta_e = 1$, $\omega_a \tau_A = 800$ case (Left) and $\beta_e = 0.01$, direct forcing case (Right).

comparable with the similar study in the framework of MHD [5]. The antenna drive may not be adequate for the current study since it directly changes reconnecting magnetic field. More thorough and systematic survey on the effects of external forcing will be the subject of a future publication.

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