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Ion and Electron Heating during Magnetic Reconnection in Weakly Collisional Plasmas

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Outline

- Magnetic reconnection is ubiquitous in fusion and astrophysical plasmas, which allows topological change of field lines, and convert field energy into plasma flow and heat. We perform a detailed analysis of ion and electron (irreversible) heating in weakly collisional plasmas.

- In weakly collisional plasmas, phase mixing processes, such as Landau damping or finite Larmor radius (FLR) effects create oscillatory structures in velocity space. Those structures suffer strong collisional dissipation.To address thermodynamic properties of such plasmas, collisional effects are essential even though collisions are rare.

- We present gyrokinetic simulations of magnetic reconnection using AstroGK. In addition to the electron heating due to parallel phase mixing in low-β plasmas as has already been shown in [1,2], ion heating is also discussed [3].

- Main results:
  - ✓ Heating occurs after most flux has reconnected. Plasmas are not directly heated by the reconnection process itself.
  - ✓ A significant fraction of the released magnetic energy, ranging from 10~50% depending on β, is converted into heat via phase mixing. (Resistive and viscous heating is small.)
  - ✓ Electron heating occurs initially along the separatrix, and later inside the island that is formed during reconnection. The electron distribution function shows parallel phase mixing structures. Parallel phase mixing is stronger for higher-β, because more electrons are in resonance with the field variations along the field lines.
  - ✓ Ion heating does not spread, and occurs at the reconnection site, and later inside the secondary island that is formed. For ions, both parallel and perpendicular phase mixing processes are active.
  - ✓ For higher-β plasmas, ion heating becomes more and more important, and becomes comparable with electron heating for β=1.

- Publications:

[1] N. F. Loureiro *et al.*, PRL 111, 025002 (2013).
[2] R. Numata and N. F. Loureiro, JPS Conf. Proc. 1, 015044 (2014).
[3] R. Numata and N. F. Loureiro, JPP, submitted.

Acknowlegements

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Simulation setup

Simulations are performed using `AstroGK` in doubly periodic slab domain.
We follow a setup for linear tearing instability study
We assume uniform background ($\nabla n_0 = \nabla T_0 = \nabla B_0 = 0$), and $\partial/\partial z = 0$.

Parameters are $k_y a = 0.8$, $\Delta' a = 23.2$, $m_i/m_e = 100$, $T_{0i}/T_{0e} = 1$, and $\rho_i/a = 0.25$.
We scan in β_e from 0.01 to 1.

Initial cond.: shifted Maxwellian electron (finite $u_{\|,e}$), non-shifted Maxwellian ion ($u_{\|,i}=0$)
→ Electron flow (amplitude and profile) is chosen to give

$$A_{\|}^{\mathrm{eq}} = \frac{A_{\|0}^{\mathrm{eq}}}{\cosh^2((x-L_x/2)/a)} S(x) \quad (S(x) \text{ is to make periodic})$$

`AstroGK` accurately reproduces the Spitzer resistivity, for which the electron-ion collision frequency (ν_{ei}) and the resistivity (η) are related by $\eta/\mu_0 = 0.380 \nu_{ei} d_e^2$.
The resistivity is recast in terms of the Lundquist number $S = 2.63\,(\nu_{ei}\tau_A)^{-1}\,(d_e a)^{-2}$
where $\tau_A = a/V_A$, V_A is the Alfvén velocity corresponding to $B_y^{\max}$.

Collision frequencies are determined to achieve the collisionless limit [3]

Heating diagnostics

To estimate plasma heating, we measure the collisional energy dissipation rate

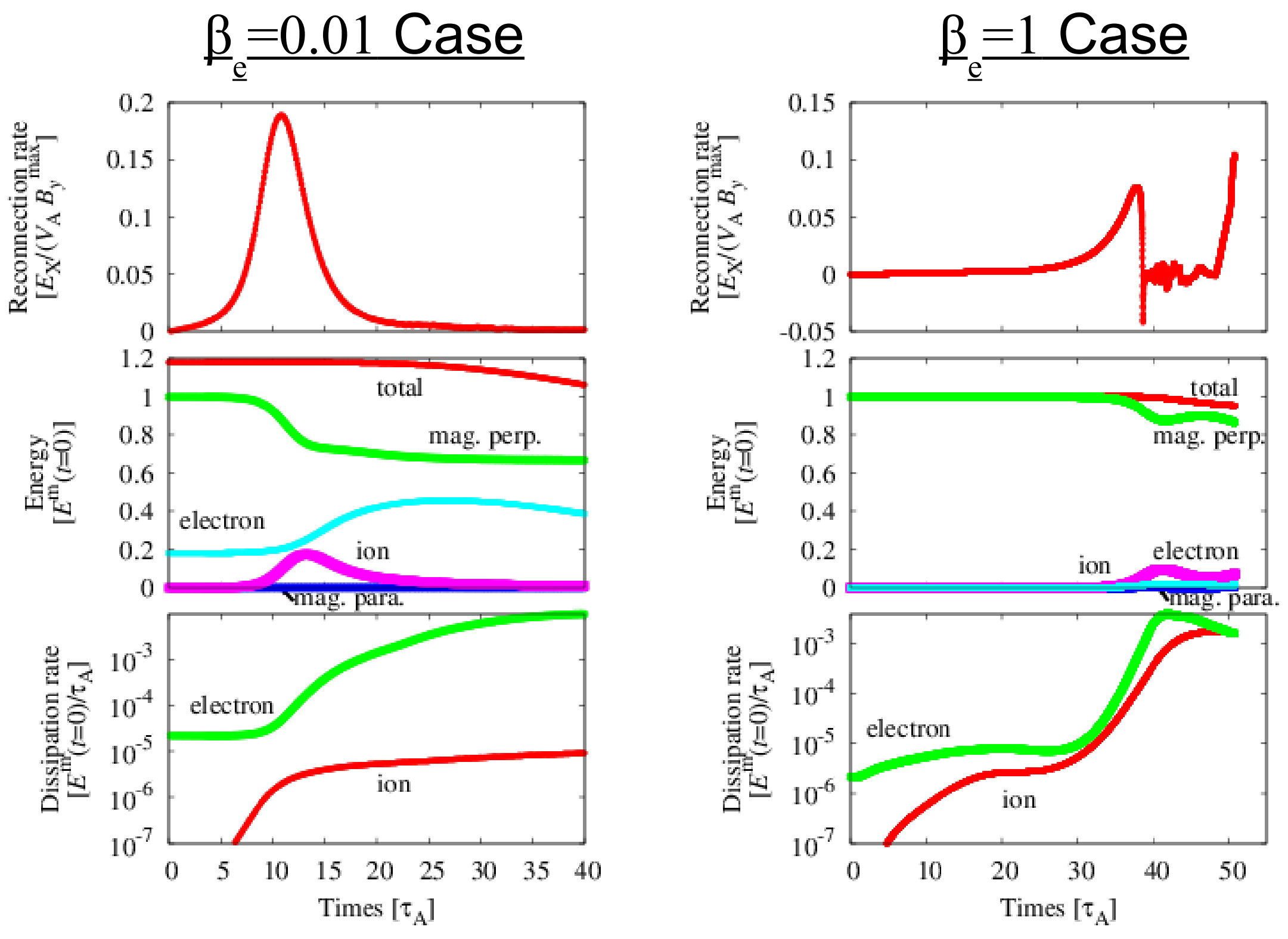
$$D_s = -\int \left\langle \frac{T_{0s} h_s}{f_{0s}} \left(\frac{\partial h}{\partial t}\right)_{\mathrm{coll}} \right\rangle_{\boldsymbol{r}} \mathrm{d}\boldsymbol{v}\, \mathrm{d}\boldsymbol{r} > 0$$

Without collisions, the gyrokinetic equation conserves the generalized energy consisting of the particle part E^{p} and the magnetic field part E^{m}

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

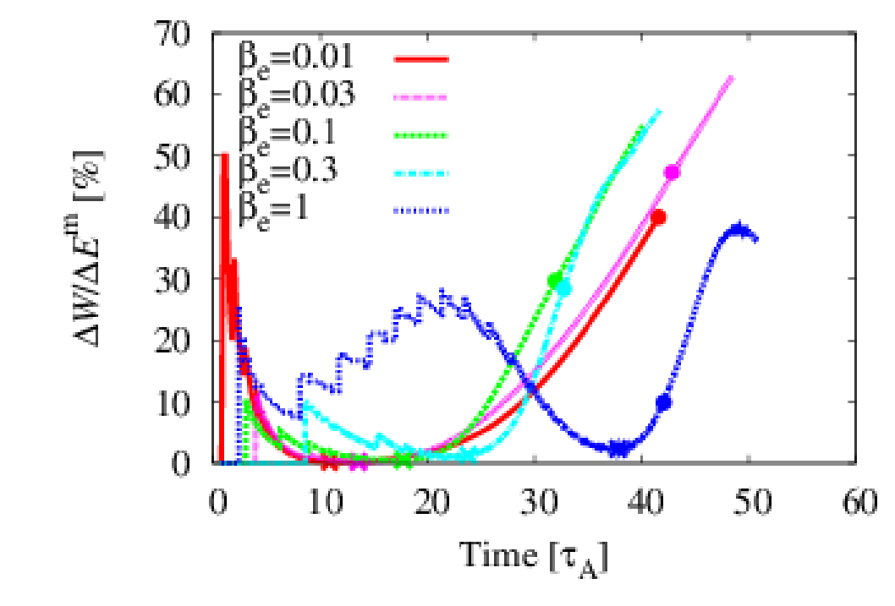
where $\delta f_s = -(q_s \varphi / T_{0s}) f_{0s} + h_s$ is the perturbation of the distribution function, and h_s is the non-Boltzmann part obeying the gyrokinetic equation, and the generalized energy is dissipated by collisions as $dW/dt = -\sum_s D_s$. The collisional dissipation increases the entropy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

Simulation Results

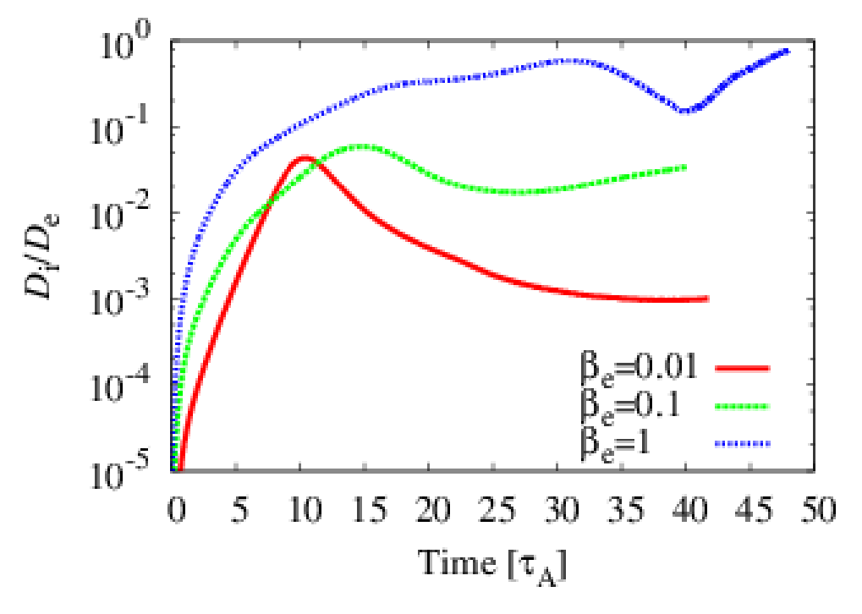


Time evolutions of reconnection rate, energy components, and dissipation rates.

- Reconnection is fast (~O(0.1))
- Time lag between the maximum of reconnection rate and dissipation rate
- Released energy is first converted to the ion kinetic energy reversibly. Electron energy gradually increases via phase mixing, and is stored in the form of temperature and higher-order moments.



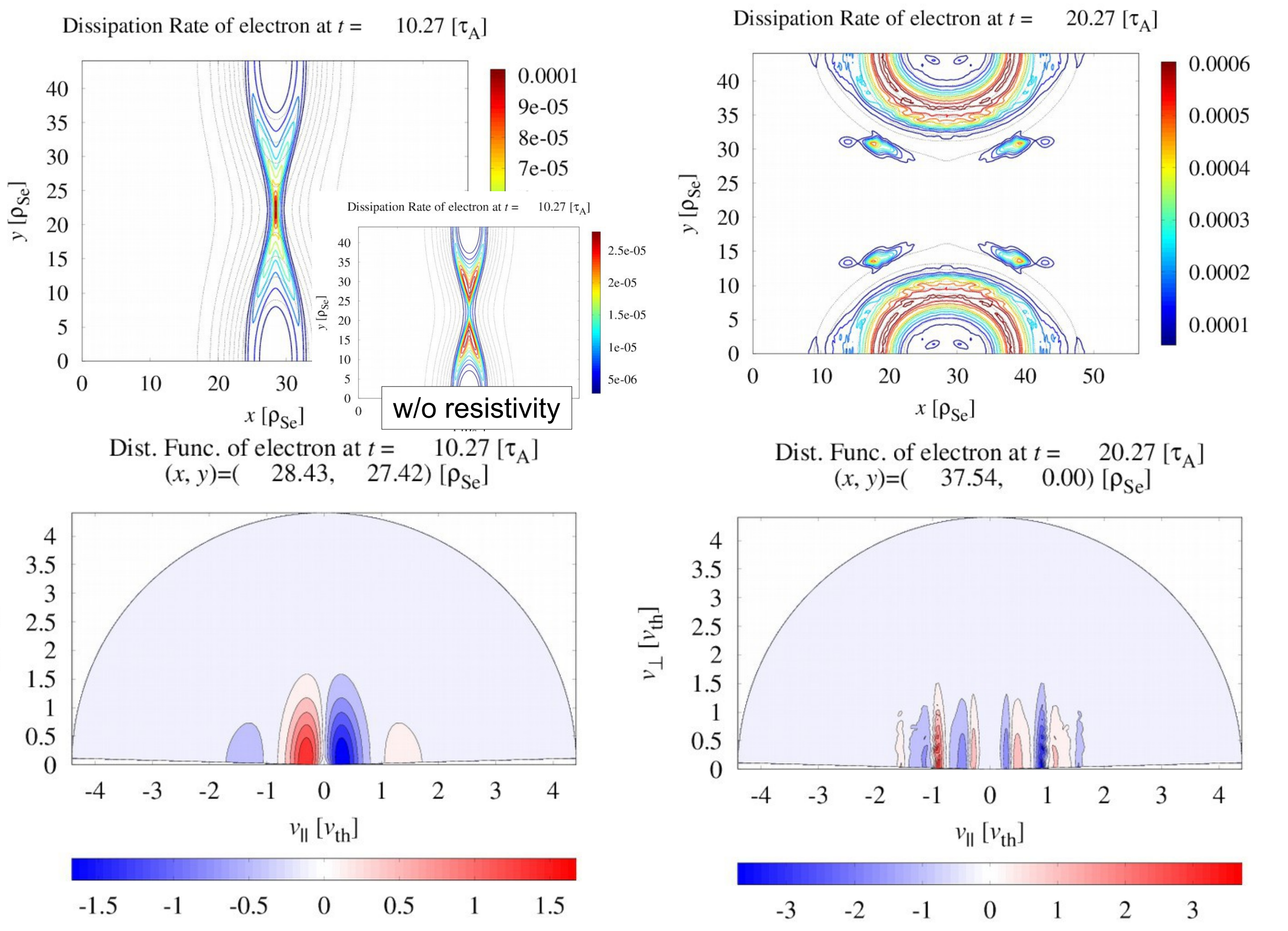
Ratio of the dissipated energy to the released magnetic energy



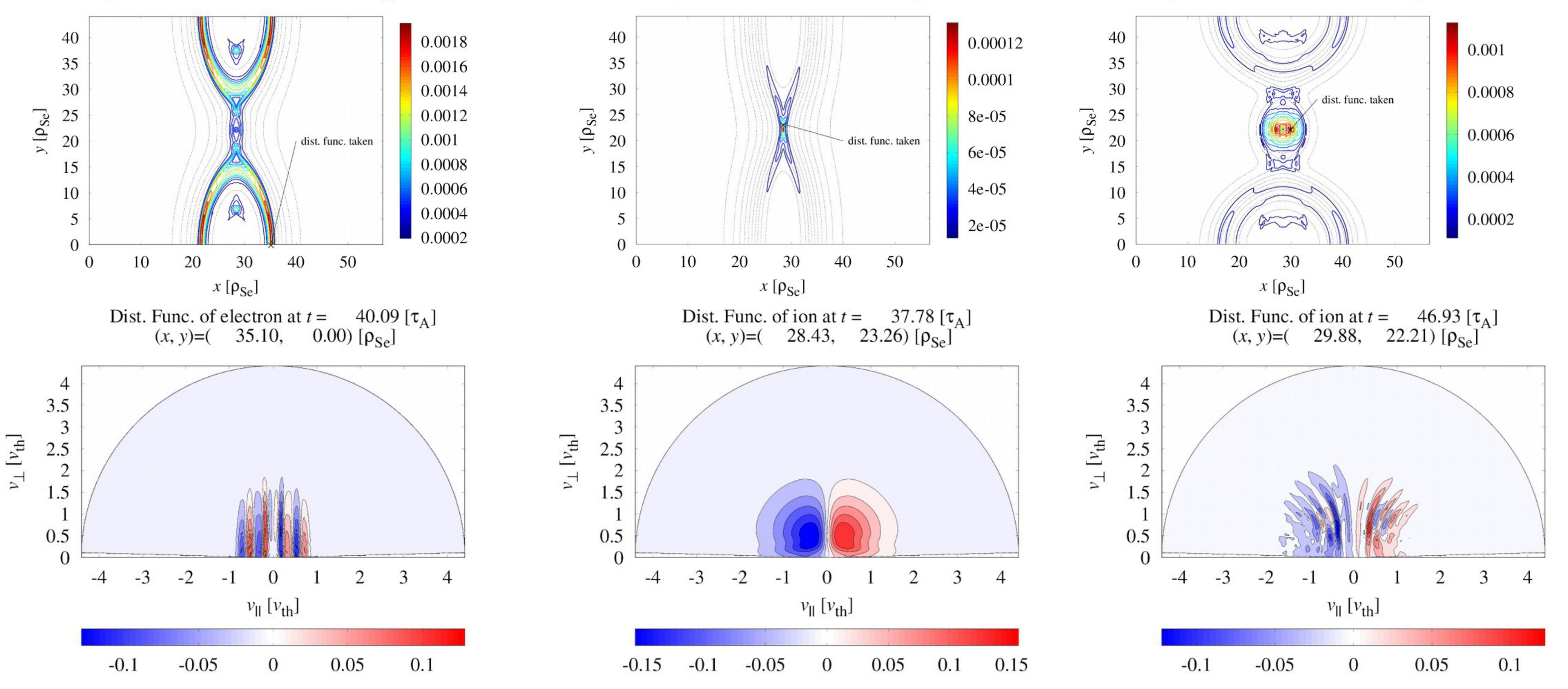
Ratio of ion to electron dissipation rate

- The energy conversion from the magnetic to thermal energy is not a monotonic function of β_e.
- The ratio of the energy dissipation rates of ions to electrons becomes approximately unity for $\beta_e=1$.

$\beta_e=0.01$ Case



$\beta_e=1$ Case



- Spatial distribution of dissipation rate, and distribution functions taken where the dissipation rate is large are shown for β_e=0.01,1.

- Electron dissipation occurs along separatrix, and later localizes inside the island.

- Electron parallel phase mixing is clearly seen where resonance condition $v_{\|} \sim V_A$ is met. More electrons are in resonance, enhancing local strength of phase mixing for higher-β_e.

- For β_e=1 case, ion heating is comparable with electron heating. Ion heating does not spread, and localizes at the center of the domain, and later in the secondary island.

- For ions, both parallel and perpendicular phase mixing is active.

- Energy dissipation due to resistivity and viscosity is small compared with that due to phase mixing.

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