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ScienceDirect
Advances in Space Research 41 (2008) 1643–1648
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Electron temperature anisotropy effects on tearing mode in ion-scale current sheets

K. Haijima [a], K.G. Tanaka [b,*], M. Fujimoto [b], I. Shinohara [b]

[a] *Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[b] *Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, Japan*

Received 27 October 2006; received in revised form 4 May 2007; accepted 14 May 2007

Abstract

Recent two-dimensional (2-D) particle-in-cell (PIC) simulations have shown that there is a critical thickness of a current sheet, above which no significant saturation amplitude of the 2-D tearing (TI) mode can be expected. Here, we have introduced the initial electron temperature anisotropy ($\alpha_{e0} = T_{e\perp}/T_{e\|} > 1$), which is known to raise significantly the linear growth rates, and inspected if $\alpha_{e0} > 1$ can change the saturation level of the TI in a super-critical current sheet. Varying α_{e0} and D (D: the current sheet half-thickness) systematically, we have found that while α_{e0} boosts up the linear growth rate in both sub- and super-critical current sheets, macroscopic effects are obtained only in sub-critical current sheets, that is, energy transfer from the fastest growing short wavelength modes to longer wavelength modes are available only in the sub-critical regime. Since the critical thickness is a fraction of the ion inertial length, the tearing mode assisted by the electron temperature anisotropy alone, despite its significant boost in the linear growth rate, cannot be the agent for reconnection triggering in a current sheet of ion-scale thickness.

Keywords: Particle-in-cell simulation; Electron temperature anisotropy; Magnetic reconnection; Magnetotail

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1. Introduction

Magnetic reconnection is one of the most important energy conversion processes in the collisionless plasma that releases the energy stored in the form of magnetic field (Priest and Forbes, 2000). In the magnetospheric environment, a number of in situ observations clarified not only its existence but also its importance in regulating the flow of mass and energy into the Earth's magnetosphere from the solar wind (Wolf, 1983). A systematic study on the process was performed by Geospace Environment Modeling (GEM) reconnection challenge (e.g. Birn et al., 2001; Shay et al., 2001; Pritchett, 2001), which investigated a standard two-dimensional (2-D) magnetic reconnection problem using a variety of simulation models ranging from full electromagnetic particle-in-cell (PIC) code to resistive MHD. The major conclusion is that all the models including Hall effects produce essentially indistinguishable fast reconnection rates independent of the dissipation mechanism. The conclusion of GEM challenge, however, is not necessary fully accepted and has been contested by a number of authors (Karimabadi et al., 2004a; Daughton et al., 2006).

Magnetic reconnection in the GEM challenge is driven by an X-line which is imposed in the initial condition and thus the problem of triggering was not addressed. The tearing mode is the most well-known candidate as the trigger agent of reconnection. The linear theory (e.g., Brittnacher et al., 1995) of the tearing instability (TI) predicts the fastest growing mode to have the wavelength $\lambda_{\max} = 12D$, where D is the initial half-thickness of the current sheet. While there is observational evidence that the magnetotail current sheet thickness becomes as thin as the relevant ion inertial length prior to substorm onsets (Sergeev et al., 1990), whether it thins further down to electron scale to initiate reconnection is an open question. Thus, it is reason-

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[*] Corresponding author. Tel.: +81 42 759 8168; fax: +81 42 759 8456.
E-mail address: tkentaro@stp.isas.jaxa.jp (K.G. Tanaka).

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doi:10.1016/j.asr.2007.05.049

able to ask if TI stays as a viable reconnection triggering agent in an ion-scale current sheet. Indeed when D is enlarged, while the linear growth rate stays nonnegligible, recent 2-D PIC simulations have shown that there is a critical thickness, above which no significant macroscopic effects by TI can be produced (Tanaka et al., 2004). Tanaka et al. (2004) have found two different critical thicknesses for two different system sizes. When the ion-to-electron temperature ratio is $T_i/T_e = 8$, the first critical thickness $D_{cr1} = 3.5\lambda_e$ is associated with the system size $L_x = \lambda_{max} = 12D$ and the second critical thickness $D_{cr2} = 2.\ 7(\lambda_i\lambda_e)^{1/2}$ is for $L_x = 2\lambda_{max} = 24D$. Here, λ_i, λ_e, and L_x are the ion and electron inertial lengths and the system size, respectively. That is, when the longer wavelength $\lambda = 2\lambda_{max}$ mode is allowed to grow, one can expect macroscopically substantial reconnection to show up only when $D < D_{cr2}$, which is as small as $\sim 0.4\lambda_i$ at the real mass ratio.

Recently the electron temperature anisotropy effect on the TI growth rate has been studied. It is known that the electron anisotropy $\alpha_{e0} = T_{e\perp}/T_{e\parallel} > 1$ not only leads to a significant boost in the TI growth rates but also shifts the fastest growing mode to the shorter wavelength mode than that of the isotropic case (Chen and Palmadesso, 1984; Karimabadi et al., 2004b). Two-dimensional PIC simulations have confirmed the boosted-up linear growth rates of short wavelength modes and demonstrated that substantial amount of reconnected flux is obtained as the smaller islands subsequently coalescence to larger islands (Karimabadi et al., 2004b).

While the above-mentioned studies suggest the remarkable capability of the electron temperature anisotropy to trigger reconnection, the lack of systematic survey does not allow us to conclude whether the effect is strong enough to overcome the limitation posed by the critical thicknesses. Because of differences in the parameters chosen between Tanaka et al. (2004), Karimabadi et al. (2004b) (especially the ion-to-electron temperature ratio), it is not clear whether the current sheet that was subject to substantial reconnection reported in Karimabadi et al. (2004b) was of sub- or super-critical thickness. In this study, while keeping the other parameters the same as in Tanaka et al. (2004), we vary α_{e0} and D to see if TI supported by the electron anisotropy effect remains as a viable triggering agent of macroscopic reconnection in super-critical current sheets.

2. Simulation setup

We study the effects of electron temperature anisotropy on TI using 2-D (two spatial dimensions and three velocity components) electromagnetic full particle code. The initial condition is the one-dimensional Harris current sheet (Harris, 1962) denoted by $B_x(z) = -B_0 \tanh(z/D)$, where D is a half-thickness of initial current sheet and B_0 is the lobe magnetic field. The initial ion temperature inside the current sheet is set to be isotropic, $T_{i,xx,CS} = T_{i,yy,CS} = T_{i,zz,CS} = T_{i,CS}$, where $T_{i,xx,CS}$, $T_{i,yy,CS}$, and $T_{i,zz,CS}$ are the diagonal components of the ion temperature tensor, respectively. On the other hand, the initial electron temperature is allowed to be anisotropic. In this study, $T_{e,yy,CS}$ and $T_{e,zz,CS}$ are expressed as $T_{e,yy,CS} = T_{e,zz,CS} = T_{e,CS}$, whereas $T_{e,xx,CS}$ is defined as $T_{e,xx,CS} = T_{e,CS}/\alpha_{e0}$. The plasma inside the current sheet has the density n_{CS} and the ion-to-electron temperature ratio $T_{i,CS}/T_{e,CS} = 8$. Hereinafter, n_{CS} and B_0 is the normalization units for the density and the electromagnetic field. The ion inertial length $\lambda_i = c/\omega_{pi}$ (c: the velocity of light, ω_{pi}: ion plasma frequency) based on n_{CS}, and the inverse of ion gyro frequency Ω_i^{-1} based on B_0 are the units for spatial and time scale, respectively. Velocities will be measured in the ion Alfvén speed unit $V_{Ai} = B_0/(4\pi m_i n_{CS})^{1/2}$, ($m_i$: the ion mass). In this normalization, the electron inertial length is $\lambda_e = M^{-1/2}$, where M is the ion-to-electron mass ratio. We set the electron plasma frequency and the gyro frequency to be the same $\omega_{pe} = \Omega_e$. ($\tau = \omega_{pe}/\Omega_e = 1$). Background plasma density $n_{BG} = 0.1n_{CS}$ is distributed outside the current sheet with the isotropic temperature $T_{i,BG} = T_{e,BG} = T_{e,CS}$. Except for the low value of τ, this setting is intended to model the near-Earth tail situation. Periodic boundary conditions are imposed in the x direction while conducting walls are set at the z boundaries. The simulation box is $[0, L_x] \times [-L_z/2, L_z/2]$ in the normalized unit, with $L_z = (2/3)L_x$. The spatial grid of $\Delta x = 0.9375\lambda_{De}$ (λ_{De}: the Debye length), and the time step of $\Delta t = 0.15625\Omega_e^{-1}$ are adopted, respectively.

3. Simulation results

3.1. $L_x = 12D$ versus $24D$ at $M = 25,\ D = 1, \alpha_{e0} = 2.0$

First we compare the results from the two cases with different system size, $L_x = 12D$ (λ_{max}) and $24D$, both at $\alpha_{e0} = 2$, $M = 25$ and $D = 1$, in order to see the effects of the system length on the nonlinear development of the magnetic reconnection. One should be reminded that no remarkable reconnection is attained at $(\alpha_{e0}, L_x) = (1, 12D)$ while substantial reconnection is achieved for the larger system $(\alpha_{e0}, L_x) = (1, 24D)$ case because $D = 1$ satisfies $D_{cr1} < D < D_{cr2}$ for $M = 25$ (Tanaka et al., 2004). In Fig. 1 the time histories of the maximum value of B_z at $z = 0$ are shown. The solid-red and dashed-red lines show $(\alpha_{e0}, L_x) = (2, 24D)$ and $(2, 12D)$ cases, respectively. Both the $L_x = 12D$ and $24D$ cases show essentially the same quick growths until $t = 12$. We have confirmed that this period corresponds to the formation of small magnetic islands. After $t = 12$, only the $L_x = 24D$ case grows all the way up to $B_z \sim 1$. In contrast, the $L_x = 12D$ case saturates at below the level of $B_z = 0.1$, with which the magnetic island width is so small to be below the initial current sheet thickness. One can conclude that the electron temperature anisotropy $\alpha_{e0} = 2$ does boost-up the initial growth phase even $D > D_{cr1}$ but it cannot lift-up the saturation level. Only by enlarging the system size to $L_x = 24D$ and allowing the $\lambda = 24D$ mode to grow, the lim-