J. Plasma Phys. (2016), *vol.* 82, 305820101 © Cambridge University Press 2016 1
doi:10.1017/S0022377816000118

'Effective' collisions in weakly magnetized collisionless plasma: importance of Pitaevski's effect for magnetic reconnection

Lev M. Zelenyi[1] **and Anton V. Artemyev**[1,2,†]

[1]Space Research Institute (IKI), 84/32 Profsoyuznaya Str, Moscow 117997, Russia

[2]Department of Earth, Planetary, and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, 603 Charles E Young Dr E, Los Angeles, CA 90095, USA

(Received 16 September 2015; revised 19 January 2016; accepted 20 January 2016)

In this paper we revisit the paradigm of space science turbulent dissipation traditionally considered as myth (Coroniti, *Space Sci. Rev.*, vol. 42, 1985, pp. 399–410). We demonstrate that due to approach introduced by Pitaevskii (*Sov. J. Expl Theor. Phys.*, vol. 44, 1963, pp. 969–979; (in Russian)) (the effect of a finite Larmor radius on a classical collision integral) dissipation induced by effective interaction with microturbulence produces a significant effect on plasma dynamics, especially in the vicinity of the reconnection region. We estimate the multiplication factor of collision frequency in the collision integral for short wavelength perturbations. For waves propagating transverse to the background magnetic field, this factor is approximately $(\rho_e k_x)^2$ with ρ_e an electron gyroradius and where k_x is a transverse wavenumber. We consider recent spacecraft observations in the Earth's magnetotail reconnection region to the estimate possible impact of this multiplication factor. For small-scale reconnection regions this factor can significantly increase the effective collision frequency produced both by lower-hybrid drift turbulence and by kinetic Alfvén waves. We discuss the possibility that the Pitaevskii's effect may be responsible for the excitation of a resistive electron tearing mode in thin current sheets formed in the outflow region of the primary X-line.

1. Introduction

There are three main triggering processes for magnetic reconnection in equilibrium collisionless plasma systems: Landau resonance of tearing mode perturbations and demagnetized ions (e.g. Schindler 1974; Galeev & Zelenyi 1976), inertia of magnetized electrons (e.g. Laval, Pellat & Vuillemin 1966; Porcelli *et al.* 2002; Zelenyi & Artemyev 2013, and references therein) and effective collisions induced by particle scattering on electromagnetic turbulence (e.g. Huba, Gladd & Papadopoulos 1977; Coroniti 1980; Büchner & Zelenyi 1987). All these three processes can drive the instability of an equilibrium (or quasi-equilibrium) current sheet and result in magnetic field reconfiguration. The situation can be much more complicated for dynamical plasma systems where the turbulent magnetic reconnection destroys (or

† Email address for correspondence: ante0226@gmail.com

reforms) current sheets and magnetic discontinuities (Servidio *et al.* 2011; Greco *et al.* 2012; Rappazzo *et al.* 2012; Karimabadi *et al.* 2013). However, in this study we concentrate on consideration of small perturbations of an equilibrium current sheet. This is typical situation for magnetic reconnection in the Earth's magnetotail where the ion Landau resonance is considered to be a main candidate for tearing mode excitation (Schindler 2006; Zelenyi *et al.* 2008; Sitnov & Swisdak 2011) where the numerous spacecraft observations have revealed the manifestations of reconnection events (e.g. Petrukovich *et al.* 1998; Baumjohann 2002; Angelopoulos *et al.* 2008; Nagai *et al.* 2011). However, many physical problems of ion (resonant) tearing mode still remain unsolved (see discussion in Pellat, Coroniti & Pritchett 1991; Quest, Karimabadi & Brittnacher 1996; Sitnov *et al.* 2002). Thus, the idea of effective dissipation induced by particle scattering due to wave–particle interaction appears to be quite promising. Previous estimates (Coroniti 1985) and modern spacecraft observations (e.g. Eastwood *et al.* 2009) were somewhat pessimistic concerning this idea – the observed level of electromagnetic turbulence appears to be insufficient to support the required effective collision conductivity in the Earth's magnetotail. In this paper, we consider an additional effect responsible for the enhancement of effective collisions. Although, we concentrate on magnetotail reconnection, the proposed effect can also be important for laboratory devices where a weakly collisional reconnection geometry is reproduced (Le *et al.* 2015).

The kinetic investigation of current sheet stability with the effects of particle effective collisions requires the consideration of the Vlasov–Maxwell equations with a collision integral (e.g. Zelenyi & Artemyev 2013, and references therein). Due to the complicated form of the full collision integral (Pitaevskii & Lifshitz 1981), the practical approach is reduced to the inclusion of an approximate form of this integral into a kinetic equation. For example, one of the most popular forms of the collision operator $Y[f]$ acting on the velocity distribution $f = f_0 + \delta f$ has been proposed by Bhatnagar, Gross & Krook (1954):

$$Y[f] = -\nu\left(\delta f - \left(\frac{n}{n_0} + \frac{m}{T}\langle \boldsymbol{v}\rangle \boldsymbol{v}\right) f_0\right), \tag{1.1}$$

where ν is Coulomb collision frequency (later treated more generally as a frequency of effective collisions due to interaction of electrons with different wave modes), m and T are the mass and temperature of the particles, f_0 and n_0 are the unperturbed velocity distribution and plasma density and

$$\left.\begin{aligned} \langle \boldsymbol{v}\rangle &= n_0^{-1}\int \boldsymbol{v}\delta f\,\mathrm{d}\boldsymbol{v} \\ n &= \int \delta f\,\mathrm{d}\boldsymbol{v}. \end{aligned}\right\} \tag{1.2}$$

We also note that $\int \boldsymbol{v} f_0\,\mathrm{d}\boldsymbol{v} = 0$ and $n_0 = \int f_0\,\mathrm{d}\boldsymbol{v}$.

The integral (1.1) describes the relaxation of the velocity distributions to the initial state f_0. This integral does not include any derivatives of the perturbation δf and thus does not take into account any information about the internal fine structure of δf. In this paper, we show how the consideration of exact form of the collision integral can modify the effective frequency ν with particle gyration in the background magnetic field produces significant modulations in the distribution function δf.

2. Collisions in a weakly magnetized plasma

To consider the effect of a finite electron gyroradius on effective collisions below we use the full expression of the Landau form of the collision integral $Y[f] = -m^{-1}(\nabla \cdot \boldsymbol{s})$ where the density of particle flux $\boldsymbol{s}$ has the following components (Pitaevskii & Lifshitz 1981):

$$\begin{aligned} s_\alpha = & \frac{\pi e^2 \Lambda}{m} \sum_\beta \int \left(\frac{\partial f(\boldsymbol{v}')}{\partial v'_\beta} + \frac{m v'_\beta}{T} f(\boldsymbol{v}') \right) f_0(\boldsymbol{v}) \frac{w^2 \delta_{\beta\alpha} - w_\alpha w_\beta}{w^2} \, \mathrm{d}\boldsymbol{v}' \\ & - \frac{\pi e^2 \Lambda}{m} \sum_\beta \int \left(\frac{\partial f(\boldsymbol{v})}{\partial v_\beta} + \frac{m v_\beta}{T} f(\boldsymbol{v}) \right) f_0(\boldsymbol{v}') \frac{w^2 \delta_{\beta\alpha} - w_\alpha w_\beta}{w^2} \, \mathrm{d}\boldsymbol{v}', \end{aligned} \tag{2.1}$$

where $\boldsymbol{w} = \boldsymbol{v} - \boldsymbol{v}'$, $\alpha, \beta = x, y, z$, $\Lambda = \ln(\lambda_D q^2/T)$ and λ_D is the Debye length.

Considering the perturbation $\delta f = f(\boldsymbol{v}) \exp(\mathrm{i}\varPhi)$ of the initial distribution function $f_0(\boldsymbol{v})$, the phase of the perturbation is $\varPhi = \boldsymbol{k} \cdot \boldsymbol{r} - \omega t$. The corresponding perturbations to the electromagnetic field are $\delta \boldsymbol{B} = \boldsymbol{B} \exp(\mathrm{i}\varPhi)$, $\delta \boldsymbol{E} = \boldsymbol{E} \exp(\mathrm{i}\varPhi)$, while the background magnetic field is $\boldsymbol{B}_0 = B_0 \boldsymbol{e}_z$. The wave vector of perturbations $\boldsymbol{k}$ is assumed to lie in the (x, z) plane. In this case, the perturbation of the Valsov equation takes the form

$$\frac{\partial \delta f}{\partial t} + \boldsymbol{v} \frac{\partial \delta f}{\partial \boldsymbol{r}} + \frac{q}{mc} [\boldsymbol{v} \times \boldsymbol{B}_0] \frac{\partial \delta f}{\partial \boldsymbol{v}} + Y[\delta f] = -\frac{q}{m} \left(\delta \boldsymbol{E} + \frac{1}{c} [\boldsymbol{v} \times \delta \boldsymbol{B}] \right) \frac{\partial f_0}{\partial \boldsymbol{v}}. \tag{2.2}$$

We introduce the force $\boldsymbol{F} = (q/m)(\boldsymbol{E} + c^{-1}[\boldsymbol{v} \times \boldsymbol{B}])$, cylindrical velocity coordinates $v_x = v_\perp \cos\theta$, $v_y = v_\perp \sin\theta$ and rewrite (2.2) as

$$-\mathrm{i}\omega \delta f + \mathrm{i} k_z v_z \delta f + \mathrm{i} k_x v_\perp \cos\theta \delta f - \frac{q B_0}{mc} \frac{\partial \delta f}{\partial \theta} + Y[\delta f] = -\frac{q}{m} \boldsymbol{F} \mathrm{e}^{\mathrm{i}\varPhi} \frac{\partial f_0}{\partial \boldsymbol{v}}, \tag{2.3}$$

where $[\boldsymbol{v} \times \boldsymbol{B}_0](\partial/\partial \boldsymbol{v}) = -B_0(\partial/\partial\theta)$. Then we divide (2.3) by $\exp(\mathrm{i}\varPhi)$ and introduce $\varOmega_0 = qB_0/mc$, $\lambda = \omega - k_z v_z$:

$$-\mathrm{i}(\lambda - k_x v_\perp \cos\theta) f - \varOmega_0 \frac{\partial f}{\partial \theta} + Y[f] = -\boldsymbol{F} \frac{\partial f_0}{\partial \boldsymbol{v}}. \tag{2.4}$$

We introduce the function $W = (\lambda\theta - k_x v_\perp \cos\theta)/\varOmega_0$ and function $g(\boldsymbol{v}) = f(\boldsymbol{v}) \exp(\mathrm{i}W)$. Thus, (2.4) can be rewritten as

$$\frac{\partial g}{\partial \theta} + \mathrm{e}^{\mathrm{i}W} Y[g \mathrm{e}^{-\mathrm{i}W}] = -\boldsymbol{F} \frac{\partial f_0}{\partial \boldsymbol{v}} \mathrm{e}^{\mathrm{i}W}. \tag{2.5}$$

To derive the dispersion relation for perturbations, one should substitute into (2.5) the Maxwell equations for electromagnetic field perturbations ($\sim \boldsymbol{F}$) expressed through function g (see, e.g. Zelenyi & Artemyev 2013). In this case, the final wave frequency/growth rate would depend on collision frequency (e.g. for the simplified collision integral (1.1) the operator Y is proportional to collision frequency ν). However, we would like to estimate the effect of a finite electron gyroradius on collision frequency ν. Thus, we compare the term $\sim Y$ for the two systems: when simplified (1.1) can be used and $Y \sim \nu$ and when the full collision integral

https://doi.org/10.1017/S0022377816000118 Published online by Cambridge University Press

$Y[f] = -m^{-1}(\nabla \cdot \boldsymbol{s})$ with (2.1) should be taken into account. For this reason, we carefully consider the second term in (2.5) and estimate the main part of this term

$$\int^{\theta} \mathrm{e}^{\mathrm{i}W} Y[g\mathrm{e}^{-\mathrm{i}W}]\,\mathrm{d}\theta. \tag{2.6}$$

In the limit $k_x\sqrt{2T/m}/\Omega_0 \gg 1$, function $g\exp(-\mathrm{i}W)$ contains the fast oscillating term $\sim \exp(\mathrm{i}k_x v_\perp \sin\theta/\Omega_0) = \exp(\mathrm{i}k_x v_y/\Omega_0)$. Thus, in (2.1) we should keep the main terms corresponding to the derivative $\partial f/\partial v_y$. The first term in (2.1) contains the integral $\int (\partial f/\partial v_y')\,\mathrm{d}v_y' \sim f$. Therefore, the second term with $\partial f/\partial v_y$ is more important and we can write:

$$s_\alpha \approx -\frac{\pi e^2 \Lambda}{m}\left(\frac{\partial f(\boldsymbol{v})}{\partial v_y} + \frac{m v_y}{T} f(\boldsymbol{v})\right) A_\alpha(\boldsymbol{v}) \tag{2.7}$$

$$A_\alpha(\boldsymbol{v}) = \int f_0(\boldsymbol{v}')\frac{w^2\delta_{y\alpha} - w_y w_\beta}{w^2}\,\mathrm{d}\boldsymbol{v}'. \tag{2.8}$$

The main part of s_α from (2.8) is

$$s_\alpha \approx -\mathrm{i}\frac{k_x}{\Omega_0}\frac{\pi e^2 \Lambda}{m} g(\boldsymbol{v})\mathrm{e}^{-\mathrm{i}W} A_\alpha(\boldsymbol{v}). \tag{2.9}$$

Thus, the integrand of (2.6) takes the form

$$\mathrm{e}^{\mathrm{i}W} Y[g\mathrm{e}^{-\mathrm{i}W}] = -\frac{k_x^2}{\Omega_0^2}\frac{\pi e^2 \Lambda}{m^2} g(\boldsymbol{v}) A_\alpha(\boldsymbol{v}). \tag{2.10}$$

In dimensionless form (2.10) can be written as

$$\mathrm{e}^{\mathrm{i}W} Y[g\mathrm{e}^{-\mathrm{i}W}] = -\frac{2k_x^2 T}{\Omega_0^2 m}\tilde{Y}[f]\mathrm{e}^{\mathrm{i}W}, \tag{2.11}$$

where $\tilde{Y}$ is the initial collision integral (2.1) without derivatives over fast oscillation terms. Equation (2.11) shows that the effect of a finite electron gyroradius provides the multiplication factor $2k_x^2T/\Omega_0^2 m$. This factor is omitted in the simplified form of the collision integral (1.1). Therefore, if we operate with the collision frequency ν from (1.1) then this expression for collision frequency ν (Coulomb or effective) should be multiplied by the term $2k_x^2T/\Omega_0^2 m \gg 1$. Of course, for a complete investigation of system stability one should consider the full collision integral (2.1), but for many applications the simplified approach with collision frequency ν can be applied with the corresponding correction $\sim 2k_x^2T/\Omega_0^2 m$. Finally, we come to the following expression for the effective collision frequency in a system with weakly magnetized electrons:

$$\nu_{eff} \approx \begin{cases} \nu (k_x\rho_e)^2 & k_x\rho_e > 1 \\ \nu & k_x\rho_e \leqslant 1, \end{cases} \tag{2.12}$$

where $\rho_e = \sqrt{2T/m}/\Omega_0$ is the electron gyroradius. Note, that (2.12) provides only a simplified estimate of the effect of electron finite gyroradius on system stability. However, this simplified expression gives us the opportunity to estimate this effect for realistic system parameters. In the next section we use the modified collision frequency (2.12) to estimate the effect of effective conductivity in the regions with weak magnetic field, in particular in the reconnection regions in near-Earth plasma systems.

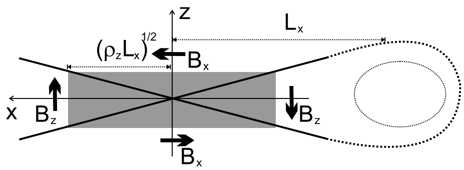

FIGURE 1. Schematic view of the X-line region.

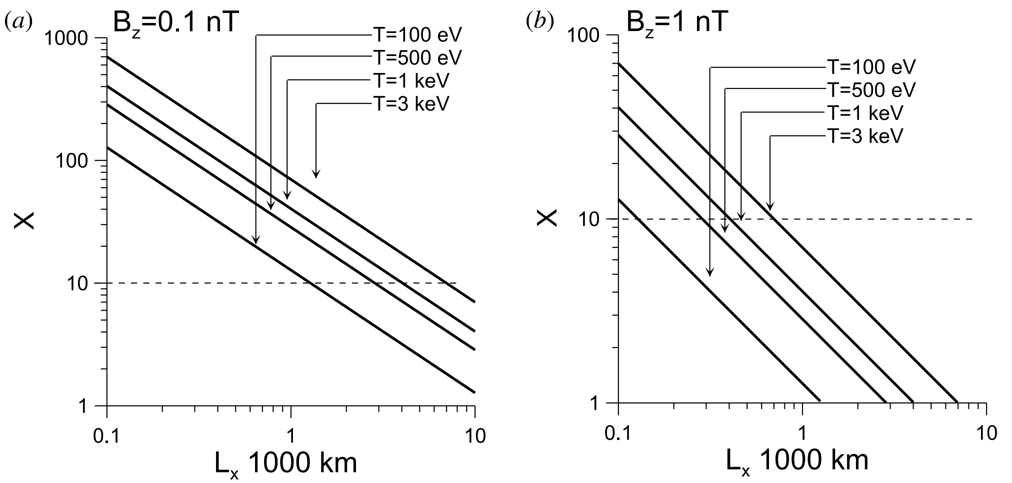

FIGURE 2. Factor X as a function of L_x for two values of B_z and four values of electron temperature T.

3. Estimates of $k_x\rho_e$ parameter for space plasma reconnection systems

Let us consider the classical 2-D X-line with magnetic field configuration $\boldsymbol{B} = B_0(z/L_z)\boldsymbol{e}_x + B_z(x/L_x)\boldsymbol{e}_z$ (see scheme in figure 1). The reversal of the B_x magnetic field component in the neutral plane $z=0$ generates so-called neutral region $|z| < \sqrt{\rho_0 L_z}$ with $\rho_0 = \sqrt{2Tmc}/eB_0$ where particles are not affected by the B_x magnetic field and can move practically freely along the y-axis (Dobrowolny 1968). The same region appears around the $x=0$ plane due to B_z reversal: $|x| < \sqrt{\rho_z L_x}$ with $\rho_z = \sqrt{2Tmc}/eB_z$. Particles, moving within this region are affected by the effective (averaged gyroradius) magnetic field with amplitude $\tilde{B}_z = B_z\sqrt{\rho_z L_x}/L_x = B_z\sqrt{\rho_z/L_x}$, while the effective particle gyroradius is equal to the spatial scale $\rho_e = \sqrt{2Tmc}/e\tilde{B}_z = \sqrt{\rho_z L_x}$. If we assume that the X-line is generated by the tearing instability with a wavelength equal to $L_x = 2\pi/k_x$ (see the scheme in figure 1), then the factor from (2.12) can be written as

$$X = (k_x\rho_e)^2 = \rho_z L_x \left(\frac{2\pi}{L_x}\right)^2 = 4\pi^2 \frac{\rho_z}{L_x}. \tag{3.1}$$

Figure 2 shows values of X as a function of electron temperature T, L_x and B_z. For the initial stage of the tearing instability (when B_z is still very small) with a wavelength L_x which is not too long the factor X is larger than one. Thus, the effect of a finite electron gyroradius can amplify energy dissipation due to effective collisions.

https://doi.org/10.1017/S0022377816000118 Published online by Cambridge University Press

To estimate the effect of the factor X on magnetic reconnection in real plasma systems we consider the effective collisions induced by two types of turbulence: lower-hybrid drift (LHD) turbulence (Huba *et al.* 1977) and kinetic Alfvén wave (KAW) turbulence (Chaston *et al.* 2009).

Wavelengths of the electromagnetic LHD mode ($\sim\rho_e\sqrt{m_i/m_e}$ (Daughton 2003)) and KAW ($<0.3\rho_e(m_i/me)$ (Voitenko 1998; Chen *et al.* 2014)) are small enough to consider these waves to be small-scale magnetic field perturbations for the large-scale reconnection process. On the other hand, these modes effectively interact both with ions (through the Cherenkov resonance $\boldsymbol{kv} = \omega$ (Karney 1978; Karimabadi *et al.* 1990; Chaston *et al.* 2014)) and electrons (through the Landau resonance $k_\parallel v_\parallel = \omega$ (Hasegawa 1976; Cairns & McMillan 2005)). Both modes are widely observed in the vicinity of the reconnection region where their contributions to the electromagnetic field turbulence are the strongest among wave modes (Eastwood *et al.* 2009; Fujimoto, Shinohara & Kojima 2011; Huang *et al.* 2012). Thus, LHD and KAW can the provide an exchange of energy between the ions and electrons, supporting the anomalous (effective) conductivity. The general form of the frequency of effective collisions ν is provided by the quasi-linear equation (Galeev & Sagdeev 1979):

$$\nu = \frac{1}{mn_0 v_D}\int W_k \frac{\Gamma(k)}{\omega(k)} k \frac{\mathrm{d}^3k}{(2\pi)^3}, \tag{3.2}$$

where v_D is particle drift velocity (i.e. en_0v_D is a current density), $\Gamma(k)$ is a wave growth/damping rate, $\omega(k)$ is a wave frequency and W_k is a wave energy density. For current sheet configurations the maximum value of ν_{LHD} was derived by Huba, Drake & Gladd (1980):

$$\nu_{LHD} \approx \frac{\omega_{pe}^2}{\omega_{LH}}\frac{E_y^2}{8\pi n_0 T_e}, \tag{3.3}$$

where ω_{pe} is the plasma frequency, $\omega_{LH} \approx \Omega_e\sqrt{m_e/m_i}$ and $\Omega_e = eB_z/m_ec$ is the electron gyrofrequency, T_e is electron temperature and E_y corresponds to the amplitude of wave electric field oscillations.

For KAW the maximum growth rate corresponds to Landau excitation $\Gamma \approx \omega/kv_D$ (Hasegawa & Mima 1978) where the wave frequency is $\omega_{KAW} = k_\parallel v_A\sqrt{1+(k_\perp\rho_i)^2}$ with ion gyroradius ρ_i and Alfvén velocity v_A (Hasegawa 1976). The corresponding collision frequency can be estimated as

$$\nu_{KAW} \approx \omega_{KAW}\Gamma\frac{\omega_{pe}^2}{k_\parallel^2 v_{Te}^2}\frac{E_y^2}{4\pi n_0 m_e v_D^2} \approx \frac{\omega_{pe}^2}{\omega_{KAW}}\frac{v_A^3}{v_D^2 v_{Ti}}\frac{E_y^2}{8\pi n_0 T_e} \approx \frac{\omega_{pe}^2}{\omega_{KAW}}\frac{E_y^2}{8\pi n_0 T_e}, \tag{3.4}$$

where we take into account that $k_\perp\rho_i \sim 1$, $v_D \sim v_{Ti} \sim v_A$.

Following Coroniti (1985), one can determine the critical amplitude of electric field energy E_y^2 necessary to organize the magnetic field dissipation within the domain with spatial scale $\sim L_z \sim \rho_i$:

$$\frac{(E_y^2)_{LHD}}{8\pi n_0 T_e} = \frac{M_A}{X}\sqrt{\frac{m_i}{m_e}}\frac{v_A v_{Ti}}{c^2} \approx \frac{M_A}{X}\sqrt{\frac{m_i}{m_e}}\left(\frac{v_A}{c}\right)^2 \tag{3.5}$$

$$\frac{(E_y^2)_{KAW}}{8\pi n_0 T_e} = \frac{M_A}{X}\frac{\omega_{KAW}}{\Omega_i}\left(\frac{v_A}{c}\right)^2 \approx \frac{M_A}{X}\left(\frac{v_A}{c}\right)^2, \tag{3.6}$$

where M_A is an Alfvén–Mach number for a particle flowing to the reconnection region. Generally $M_A \sim 0.1$ for magnetospheric physics, while $(v_A/c)^2 \approx 10^{-5}$ for the Earth's magnetotail. Equation (3.6) shows that one can decrease the estimate for the critical amplitude of wave electric field proportionally to $\sim 1/\sqrt{X} \sim 1/3$–$1/10$ (see figure 2) after taking into account the Pitaevskii effect. For magnetotail current sheets the typical amplitude of LHD waves can reach 10 mV m^{-1} (Eastwood *et al.* 2009; Fujimoto *et al.* 2011; Norgren *et al.* 2012), while the estimate of the amplitude from (3.6) is $\sqrt{(E_y^2)_{LHD}} \sim 30/\sqrt{X}$ mV m^{-1} (Coroniti 1985). Thus, a factor $X \sim 10$ can help to produce the necessary magnetic energy dissipation due to effective collisions. Amplitudes of KAW electric field are often weaker $\sim$1 mV m^{-1} (Chaston *et al.* 2012). The critical amplitude for KAW is $\sqrt{(E_y^2)_{KAW}}$ is of the order of $\sim 1/\sqrt{X}$ mV m^{-1}. The Pitaevskii effect of reducing the estimate (3.6) 2–3 times demonstrates an important role of KAW in running magnetic reconnection. Therefore, we conclude that in realistic magnetotail conditions for both cases (LHDI and KAW) the effect of finite electron gyroradius can increase effective collisions and help to overturn Coroniti (1985) objections.

4. Discussion and conclusions

The additional effect of the enhancement of effective collisions for $k\rho_e > 1$ perturbations was taken into account in the analysis of the electron resistive tearing mode (Zelenyi & Taktakishvili 1981). This mode is excited by $\nu \neq 0$ with the growth rate $\gamma = \nu \mathrm{X}(\gamma_0/k_x\sqrt{2T_e m_e})$ where $\gamma_0/k_x\sqrt{2T_e m_e} = 2\pi^{-1/2}(\rho_e/L_z)^{3/2}(1 - k_x^2 L_z^2)/k_x L_z$ is the growth rate of the electron tearing mode (Laval *et al.* 1966; Galeev & Sudan 1985). Therefore, for X factor high enough, the growth rate of the resistive tearing mode increases. This mode is produced by effective collisions and cannot be stabilized by electron magnetization (in contrast to the classical electron tearing mode (Schindler 1974; Galeev & Zelenyi 1976)). Moreover, for a tearing mode with $k\rho_e > 1$ the WKB approximation in the investigation of current sheet stability can be safely applied (Lembege & Pellat 1982) supporting the validity of the expressions for the growth rates γ and γ_0 derived for the case where the wavelength is not too long.

Effective collisions are often considered in numerical models of magnetic reconnection as a trigger for the reconnection process (Daughton, Lapenta & Ricci 2004; Daughton *et al.* 2011; Karimabadi *et al.* 2013). In this case, estimates of the reconnection rate can be based on the classical theory of an effective conductivity (Galeev & Sudan 1985; Yoon & Lui 2006) with a proper estimate for the effective collision rate. Thus, the effect of fine structured velocity distributions (when $\rho k_x > 1$) can be very important. The same effect can be provided by numerical resistivity which supports the slow growth of magnetic islands when the tearing instability is saturated by nonlinear effects (Lipatov & Zelenyi 1982).

Figure 2 shows that the most pronounced effect of a finite electron gyroradius corresponds to small-scale reconnection (i.e. small L_x) where instead of one large-scale X-line we deal with a chain of small-scale magnetic islands. Indeed, strong anisotropy of electrons accelerated in the primary reconnection region generates high-amplitude curvature currents (Egedal, Le & Daughton 2013; Artemyev *et al.* 2015) responsible for the formation of very thin current sheets with vanishing B_z magnetic field (Nakamura *et al.* 2006; Artemyev *et al.* 2013; Le *et al.* 2014). Instability of such thin current sheets results in secondary reconnection in the outflow region of the primary large-scale X-line (so-called plasmoid instability) with the corresponding birth of a

https://doi.org/10.1017/S0022377816000118 Published online by Cambridge University Press

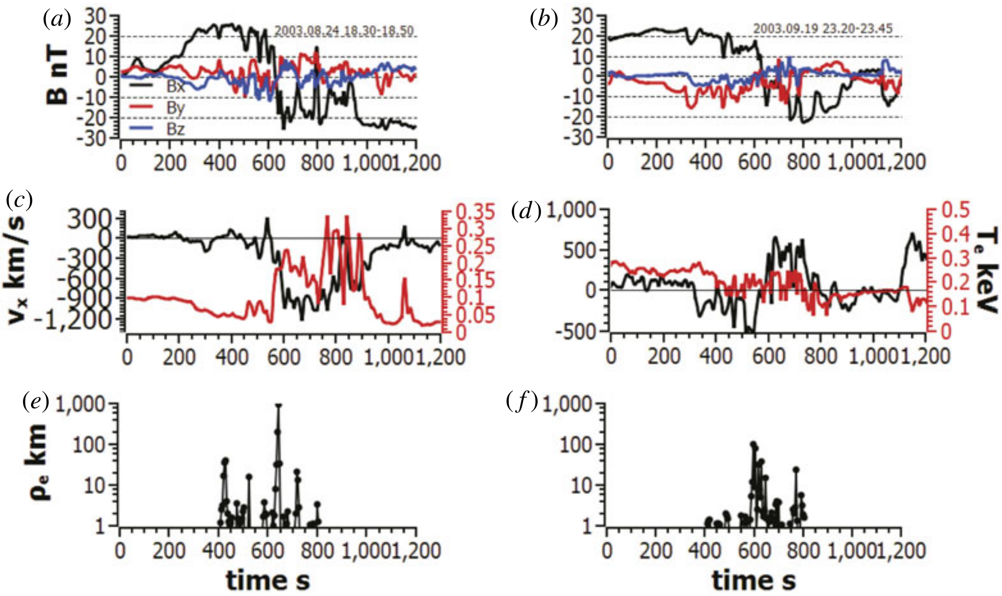

FIGURE 3. Two cases of Cluster spacecraft crossing a reconnection region (see the characteristic reversal of B_z). Both cases are taken from Artemyev *et al.* (2015).

multitude of small-scale X- and O-magnetic points (Daughton *et al.* 2011; Huang, Bhattacharjee & Forbes 2013). Thus, the secondary reconnection of such thin current sheets can occur within the region of $k_x\rho_e > 1$. To illustrate this scenario we show two events of Cluster spacecraft observations of magnetic reconnection in the Earth's magnetotail (see figure 3). The characteristic B_z reversal and plasma flows v_x indicate that Cluster is in close vicinity to the X-line. We calculate the electron gyroradius ρ_e using local measurements of the B_z and B_y magnetic field (B_x is assumed to be zero). Around the X-line ρ_e reaches $\sim$1000 km, thus X becomes larger than one for $L_x < 6R_E$. For example, the secondary reconnection with a wavelength of approximately $\sim 2R_E$ corresponds to an increase of effective collision frequency by a factor $X \sim 3$. We also note that for both events shown in figure 3, current sheet thicknesses were approximately $\sim$800 km and $\sim$600 km (see estimates of current density amplitudes in Artemyev *et al.* 2015). Thus, for $L_x \sim 2R_E$ the ratio $L_x/L_z \sim 18$ and the corresponding current sheets are very prolonged and stretched.

To conclude, we consider the effects of a finite electron gyroradius for current sheet stability in the case when effective collisions are present in the system. Following Pitaevskii (1963) we demonstrate that a fast electron gyrorotation results in a fine structure of the perturbations of the electron distribution function. As a result, the full expression for the collision integral gives a multiplication factor $\mathrm{X} \sim (k_x\rho_e)^2$ for collision frequency (where k_x is a transverse wavenumber). For realistic conditions in the Earth's magnetotail this factor can often be larger than one and thus can increase the effect of particle scattering by electromagnetic turbulence. We show that effect of a finite electron gyroradius should be particularly strong for the secondary reconnection of very thin current sheets formed in the outflow region of the primary X-line.

https://doi.org/10.1017/S0022377816000118 Published online by Cambridge University Press

Acknowledgement

Work of A.V.A. was supported by Russian Scientific Foundation (project no. 14-12-00824).

REFERENCES

ANGELOPOULOS, V., MCFADDEN, J. P., LARSON, D., CARLSON, C. W., MENDE, S. B., FREY, H., PHAN, T., SIBECK, D. G., GLASSMEIER, K.-H., AUSTER, U. *et al.* 2008 Tail reconnection triggering substorm onset. *Science* **321**, 931–935.

ARTEMYEV, A. V., PETRUKOVICH, A. A., FRANK, A. G., NAKAMURA, R. & ZELENYI, L. M. 2013 Intense current sheets in the magnetotail: peculiarities of electron physics. *J. Geophys. Res.* **118**, 2789–2799.

ARTEMYEV, A. V., PETRUKOVICH, A. A., NAKAMURA, R. & ZELENYI, L. M. 2015 Statistics of intense dawn-dusk currents in the Earth's magnetotail. *J. Geophys. Res.* **120**, 3804–3820.

BAUMJOHANN, W. 2002 Modes of convection in the magnetotail. *Phys. Plasmas* **9**, 3665–3667.

BHATNAGAR, P. L., GROSS, E. P. & KROOK, M. 1954 A model for collision processes in gases. I. Small amplitude processes in charged and neutral one-component systems. *Phys. Rev.* **94**, 511–525.

BÜCHNER, J. & ZELENYI, L. M. 1987 Chaotization of the electron motion as the cause of an internal magnetotail instability and substorm onset. *J. Geophys. Res.* **92**, 13456–13466.

CAIRNS, I. H. & MCMILLAN, B. F. 2005 Electron acceleration by lower hybrid waves in magnetic reconnection regions. *Phys. Plasmas* **12**, 102110.

CHASTON, C. C., BONNELL, J. W., CLAUSEN, L. & ANGELOPOULOS, V. 2012 Energy transport by kinetic-scale electromagnetic waves in fast plasma sheet flows. *J. Geophys. Res.* **117**, 9202.

CHASTON, C. C., BONNELL, J. W., WYGANT, J. R., MOZER, F., BALE, S. D., KERSTEN, K., BRENEMAN, A. W., KLETZING, C. A., KURTH, W. S., HOSPODARSKY, G. B. *et al.* 2014 Observations of kinetic scale field line resonances. *Geophys. Res. Lett.* **41**, 209–215.

CHASTON, C. C., JOHNSON, J. R., WILBER, M., ACUNA, M., GOLDSTEIN, M. L. & REME, H. 2009 Kinetic Alfvén wave turbulence and transport through a reconnection diffusion region. *Phys. Rev. Lett.* **102**, 015001.

CHEN, L., WU, D. J., ZHAO, G. Q., TANG, J. F. & HUANG, J. 2014 Excitation of kinetic Alfvén waves by fast electron beams. *Astrophys. J.* **793**, 13.

CORONITI, F. V. 1980 On the tearing mode in quasi-neutral sheets. *J. Geophys. Res.* **85**, 6719–6728.

CORONITI, F. V. 1985 Space plasma turbulent dissipation – Reality or myth? *Space Sci. Rev.* **42**, 399–410.

DAUGHTON, W. 2003 Electromagnetic properties of the lower-hybrid drift instability in a thin current sheet. *Phys. Plasmas* **10**, 3103–3119.

DAUGHTON, W., LAPENTA, G. & RICCI, P. 2004 Nonlinear evolution of the lower-hybrid drift instability in a current sheet. *Phys. Rev. Lett.* **93**, 105004.

DAUGHTON, W., ROYTERSHTEYN, V., KARIMABADI, H., YIN, L., ALBRIGHT, B. J., BERGEN, B. & BOWERS, K. J. 2011 Role of electron physics in the development of turbulent magnetic reconnection in collisionless plasmas. *Nat. Phys.* **7**, 539–542.

DOBROWOLNY, M. 1968 Instability of a neutral sheet. *Nuovo Cimento* B **55**, 427–442.

EASTWOOD, J. P., PHAN, T. D., BALE, S. D. & TJULIN, A. 2009 Observations of turbulence generated by magnetic reconnection. *Phys. Rev. Lett.* **102**, 035001.

EGEDAL, J., LE, A. & DAUGHTON, W. 2013 A review of pressure anisotropy caused by electron trapping in collisionless plasma, and its implications for magnetic reconnection. *Phys. Plasmas* **20**, 061201.

FUJIMOTO, M., SHINOHARA, I. & KOJIMA, H. 2011 Reconnection and waves: a review with a perspective. *Space Sci. Rev.* **160**, 123–143.

GALEEV, A. A. & SAGDEEV, R. Z. 1979 Nonlinear plasma theory. In *Reviews of Plasma Physics* (ed. A. M. A. Leontovich), vol. 7, p. 1. Springer.

GALEEV, A. A. & SUDAN, R. N. 1985 Basic plasma physics II. In *Handbook of Plasma Physics*, vol. 2. Elsevier.

GALEEV, A. A. & ZELENYI, L. M. 1976 Tearing instability in plasma configurations. *Sov. J. Expl Theor. Phys.* **43**, 1113.

GRECO, A., VALENTINI, F., SERVIDIO, S. & MATTHAEUS, W. H. 2012 Inhomogeneous kinetic effects related to intermittent magnetic discontinuities. *Phys. Rev.* E **86**, 066405.

HASEGAWA, A. 1976 Particle acceleration by MHD surface wave and formation of aurora. *J. Geophys. Res.* **81**, 5083–5090.

HASEGAWA, A. & MIMA, K. 1978 Anomalous transport produced by kinetic Alfvén wave turbulence. *J. Geophys. Res.* **83**, 1117–1123.

HUANG, S. Y., ZHOU, M., SAHRAOUI, F., VAIVADS, A., DENG, X. H., ANDRÉ, M., HE, J. S., FU, H. S., LI, H. M., YUAN, Z. G. *et al.* 2012 Observations of turbulence within reconnection jet in the presence of guide field. *Geophys. Res. Lett.* **39**, 11104.

HUANG, Y.-M., BHATTACHARJEE, A. & FORBES, T. G. 2013 Magnetic reconnection mediated by hyper-resistive plasmoid instability. *Phys. Plasmas* **20**, 082131.

HUBA, J. D., DRAKE, J. F. & GLADD, N. T. 1980 Lower-hibrid-drift instability in field reversed plasmas. *Phys. Fluids* **23**, 552–561.

HUBA, J. D., GLADD, N. T. & PAPADOPOULOS, K. 1977 The lower-hybrid-drift instability as a source of anomalous resistivity for magnetic field line reconnection. *Geophys. Res. Lett.* **4**, 125–126.

KARIMABADI, H., AKIMOTO, K., OMIDI, N. & MENYUK, C. R. 1990 Particle acceleration by a wave in a strong magnetic field – Regular and stochastic motion. *Phys. Fluids* B **2**, 606–628.

KARIMABADI, H., ROYTERSHTEYN, V., DAUGHTON, W. & LIU, Y.-H. 2013 Recent evolution in the theory of magnetic reconnection and its connection with turbulence. *Space Sci. Rev.* **178**, 307–323.

KARNEY, C. F. F. 1978 Stochastic ion heating by a lower hybrid wave. *Phys. Fluids* **21**, 1584–1599.

LAVAL, G., PELLAT, R. & VUILLEMIN, M. 1966 Instabilités électromagnétiques des plasmas sans collisions (CN-21/71). In *Plasma Physics and Controlled Nuclear Fusion Research*, vol. II, pp. 259–277. International Atomic Energy Agency.

LE, A., EGEDAL, J., DAUGHTON, W., ROYTERSHTEYN, V., KARIMABADI, H. & FOREST, C. 2015 Transition in electron physics of magnetic reconnection in weakly collisional plasma. *J. Plasma Phys.* **81**, 30108.

LE, A., EGEDAL, J., NG, J., KARIMABADI, H., SCUDDER, J., ROYTERSHTEYN, V., DAUGHTON, W. & LIU, Y.-H. 2014 Current sheets and pressure anisotropy in the reconnection exhaust. *Phys. Plasmas* **21**, 012103.

LEMBEGE, B. & PELLAT, R. 1982 Stability of a thick two-dimensional quasineutral sheet. *Phys. Fluids* **25**, 1995–2004.

LIPATOV, A. S & ZELENYI, L. M. 1982 The study of magnetic islands dynamics. *Plasma Phys.* **24**, 1082–1089.

NAGAI, T., SHINOHARA, I., FUJIMOTO, M., MATSUOKA, A., SAITO, Y. & MUKAI, T. 2011 Construction of magnetic reconnection in the near-Earth magnetotail with Geotail. *J. Geophys. Res.* **116**, 4222.

NAKAMURA, R., BAUMJOHANN, W., RUNOV, A. & ASANO, Y. 2006 Thin current sheets in the magnetotail observed by cluster. *Space Sci. Rev.* **122**, 29–38.

NORGREN, C., VAIVADS, A., KHOTYAINTSEV, Y. V. & ANDRÉ, M. 2012 Lower hybrid drift waves: space observations. *Phys. Rev. Lett.* **109** (5), 055001.

PELLAT, R., CORONITI, F. V. & PRITCHETT, P. L. 1991 Does ion tearing exist? *Geophys. Res. Lett.* **18**, 143–146.

PETRUKOVICH, A. A., SERGEEV, V. A., ZELENYI, L. M., MUKAI, T., YAMAMOTO, T., KOKUBUN, S., SHIOKAWA, K., DEEHR, C. S., BUDNICK, E. Y., BÜCHNER, J. *et al.* 1998 Two spacecraft observations of a reconnection pulse during an auroral breakup. *J. Geophys. Res.* **103**, 47–60.

PITAEVSKII, L. P 1963 Effect of collisions on perturbation of body rotating in plasma. *Sov. J. Expl Theor. Phys.* **44**, 969–979; (in Russian).

PITAEVSKII, L. P. & LIFSHITZ, E. M. 1981 *Physical Kinetics*, vol. 10. Pergamon.

https://doi.org/10.1017/S0022377816000118 Published online by Cambridge University Press

PORCELLI, F., BORGOGNO, D., CALIFANO, F., GRASSO, D., OTTAVIANI, M. & PEGORARO, F. 2002 Recent advances in collisionless magnetic reconnection. *Plasma Phys. Control. Fusion* **44**, B389.

QUEST, K. B., KARIMABADI, H. & BRITTNACHER, M. 1996 Consequences of particle conservation along a flux surface for magnetotail tearing. *J. Geophys. Res.* **101**, 179–184.

RAPPAZZO, A. F., MATTHAEUS, W. H., RUFFOLO, D., SERVIDIO, S. & VELLI, M. 2012 Interchange reconnection in a turbulent Corona. *Astrophys. J. Lett.* **758**, L14.

SCHINDLER, K. 1974 A theory of the substorm mechanism. *J. Geophys. Res.* **79**, 2803–2810.

SCHINDLER, K. 2006 *Physics of Space Plasma Activity*. Cambridge University Press.

SERVIDIO, S., DMITRUK, P., GRECO, A., WAN, M., DONATO, S., CASSAK, P. A., SHAY, M. A., CARBONE, V. & MATTHAEUS, W. H. 2011 Magnetic reconnection as an element of turbulence. *Nonlinear Process. Geophys.* **18**, 675–695.

SITNOV, M. I., SHARMA, A. S., GUZDAR, P. N. & YOON, P. H. 2002 Reconnection onset in the tail of Earth's magnetosphere. *J. Geophys. Res.* **107**, 1256.

SITNOV, M. I. & SWISDAK, M. 2011 Onset of collisionless magnetic reconnection in two-dimensional current sheets and formation of dipolarization fronts. *J. Geophys. Res.* **116**, 12216.

VOITENKO, Y. M. 1998 Excitation of kinetic Alfvén waves in a flaring loop. *Sol. Phys.* **182**, 411–430.

YOON, P. H. & LUI, A. T. Y. 2006 Quasi-linear theory of anomalous resistivity. *J. Geophys. Res.* **111**, 2203.

ZELENYI, L. & ARTEMYEV, A. 2013 Mechanisms of spontaneous reconnection: from magnetospheric to fusion plasma. *Space Sci. Rev.* **178**, 441–457.

ZELENYI, L. M., ARTEMYEV, A. V., MALOVA, H. V. & POPOV, V. Y. 2008 Marginal stability of thin current sheets in the Earth's magnetotail. *J. Atmos. Sol. Terr. Phys.* **70**, 325–333.

ZELENYI, L. M. & TAKTAKISHVILI, A. L. 1981 The influence of dissipative processes on the development of the tearing mode in current sheets. *Sov. J. Plasma Phys.* **7**, 1064–1075.