Role of electron temperature anisotropy in the onset of magnetic reconnection

H. Karimabadi

Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, California, USA

W. Daughton

Los Alamos National Laboratory, Los Alamos, New Mexico, USA

K. B. Quest

Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, California, USA

Received 19 June 2004; revised 5 August 2004; accepted 24 August 2004; published 16 September 2004.

[1] Predictions of tearing saturation in a neutral sheet range from minute amplitude to explosive growth. It is shown that in 2D, single island tearing saturates at very small amplitudes due to preferential electron heating in the parallel direction. However, the presence of multiple unstable modes allows the system to get past the stabilization and grow to ion scales. In 3D there are two current aligned instabilities that can affect the tearing mode. One is the Weibel instability driven by electron anisotropy $T_{\perp e}/T_{\|e} < 1$ and the other is the lower hybrid drift instability (LHDI). The Weibel instability is shown to at most increase the single island tearing saturation amplitude up to the singular layer thickness. On the other hand, recent studies suggest that LHDI can affect tearing through the generation of $T_{\perp e}/T_{\|e} > 1$ within the current layer. In this limit, the parallel Weibel instability merges with tearing to give rise to anisotropic tearing, which becomes the dominant electron anisotropy driven mode with a broad angular spectrum. The level of electron anisotropy generated by the LHDI can significantly enhance the tearing growth rate and extend the spectrum to very short wavelength which expedites the transition to large scale reconnection. Thus LHDI's main contribution to reconnection onset is not through anomalous resistivity but through its effect on tearing mode. *INDEX TERMS:* 7835 Space Plasma Physics: Magnetic reconnection; 7843 Space Plasma Physics: Numerical simulation studies; 7871 Space Plasma Physics: Waves and instabilities. **Citation:** Karimabadi, H., W. Daughton, and K. B. Quest (2004), Role of electron temperature anisotropy in the onset of magnetic reconnection, *Geophys. Res. Lett.*, *31*, L18801, doi:10.1029/2004GL020791.

1. Introduction

[2] The collisionless tearing mode is generally considered as the onset mechanism for reconnection at the earth's magnetopause and in the magnetotail but surprisingly, the nonlinear evolution and saturation mechanism are not well understood even in the anti-parallel regime. Note that the anti-parallel regime, which is the optimal reconnection geometry, forms the basis of all reconnection studies. The theoretical predictions range from very small saturation amplitudes [*Biskamp et al.*, 1970] to explosive growth [*Galeev et al.*, 1978]. However, one issue that is clear is that tearing is highly sensitive to the presence of electron temperature anisotropy. It becomes linearly stabilized if [*Forslund*, 1968]:

$$(1 - \alpha) > \rho_e/L \tag{1}$$

where $\alpha \equiv T_{\perp e}/T_{\|e}$ is the electron anisotropy, ρ_e is the electron gyroradius and L is the half-thickness of the current sheet. Here we address the saturation mechanism of the tearing mode using full particle simulations. The results indicate the saturation is due to parallel electron heating associated with the tearing mode. This leads to the possibility of triggering the current aligned Weibel instability driven by $\alpha < 1$ [e.g., *Laval and Pellat*, 1968; *Coppi and Rosenbluth*, 1968] which could in turn isotropize the electrons. However, we find that even in case of electron isotropization, the single island tearing saturates at amplitudes at most up to the singular layer thickness. As such, single mode tearing would not be relevant for reconnection in the magnetosphere. However, we note that the presence of even a small electron anisotropy $\alpha > 1$ may alter this conclusion. This is because $\alpha > 1$ significantly increases the growth rate of tearing [e.g., *Forslund*, 1968], and extends the unstable spectrum to very short wavelengths, thus allowing multi-unstable modes to interact which may trigger large scale reconnection [*Ricci et al.*, 2004]. However, it has been traditionally argued [e.g., *Burkhart and Chen*, 1989] that any electron anisotropy with $\alpha > 1$ would be rapidly isotropized due to various instabilities before it can affect the reconnection process. But there are at least three reasons to question this conclusion. First, it is not clear if there exist other electron anisotropy driven instabilities that can compete with anisotropic tearing within the neutral sheet. Second, some observations [*Gosling et al.*, 1989] have reported $\alpha > 1$ in the magnetosheath. Third, recent simulations at realistic mass ratio indicate (W. Daughton, et al., Nonlinear evolution of the lower-hybrid drift instability in a current sheet, submitted to *Physical Review Letters*, 2004, hereinafter referred to as Daughton et al., submitted manuscript, 2004) that the lower hybrid instability (LHDI) can rapidly generate $\alpha \sim 1.1$ within the current sheet. Motivated by these facts, we re-examine the stability of current sheets. The main questions that we want to address are: (i) what is the saturation mechanism of the tearing instability? (ii) Can $\alpha > 1$ be maintained long enough

0094-8276/04/2004GL020791$05.00

for anisotropic tearing to operate? (iii) Can anisotropic tearing get past the small saturation amplitudes and into the ion regime?

2. Linear Modes of an Anisotropic Sheet

[3] Our starting point is the well-known Harris equilibrium $B = B_{xo}\tanh(z/L)\hat{x}$ extended to the anisotropic regime. Several instabilities within a current sheet can generate electron anisotropies. The tearing mode leads to preferential heating of electrons in the parallel direction due to the fact that it has an electric field parallel to the magnetic field. On the other hand, the nonlinear evolution of lower hybrid drift instability (LHDI) can give rise to perpendicular electron heating in the central region of the sheet (Daughton et al., submitted manuscript, 2004). The resulting anisotropies can then drive other instabilities which will try to isotropize the electrons. In order to understand the interplay between the various modes, we first consider the linear properties of the electron anisotropy driven instabilities within the current sheet. There are distinct instabilities depending on whether α is larger or smaller than unity. In a homogeneous magnetized plasma, when $\alpha > 1$ there are the whistler anisotropy (WAI) [e.g., *Gary*, 1993] and electron mirror instabilities. The WAI is a cyclotron resonant mode and cannot exist within the current layer, while the electron mirror mode is an obliquely propagating electromagnetic mode with zero frequency in the electron rest frame. In the unmagnetized limit, both modes reduce to the Weibel instability [*Weibel*, 1959], with wavevector in the direction of the cooler temperature. In an anisotropic current sheet, the Weibel, and tearing become closely linked as we now demonstrate. When $\alpha > 1$, both the tearing and Weibel instabilities have wavevector parallel to the magnetic field and zero real frequency. To show the linkage between Weibel and tearing, we have derived the dispersion relation in the parallel direction (for details, see H. Karimabadi et al., Physics of saturation of kinetic instabilities in anisotropic current sheets, manuscript in preparation, 2004) which in the limit of weak resonance and moderate anisotropy can be cast as:

$$\underbrace{-\nu\tan(\nu)}_{Weibel} = \underbrace{\frac{1+2n}{2} - \sqrt{A}\frac{K_{n+1}(\sqrt{A})}{K_n(\sqrt{A})}}_{''Tearing''} \tag{2}$$

$$\nu = \left(\frac{\beta_e}{2\varepsilon_e}\right)^{1/2}\left[\left(\frac{T_{\perp e}}{T_{\|e}} - 1\right) - \frac{T_{\perp e}}{_{\|e}}\frac{\sqrt{\pi}\gamma}{ka_{\|e}} - \left(\frac{kc}{\omega_{pe}}\right)^2\right]^{1/2} \tag{3}$$

$$A = \frac{2}{3}\varepsilon_e\beta_e\left[\left(\frac{T_{\perp e}}{T_{\|e}} - 1\right) - \frac{\sqrt{\pi}\gamma}{ka_{\|e}}\right] - \varepsilon_e + \frac{\beta_e}{2\varepsilon_e}\left(\frac{kc}{\omega_{pe}}\right)^2 \tag{4}$$

$$B = \beta_e\left[\left(\frac{T_{\perp e}}{T_{\|e}} - 1\right) - \frac{\sqrt{\pi}\gamma}{ka_{\|e}}\right] \tag{5}$$

$$n = \frac{\sqrt{1-4B}}{2} \tag{6}$$

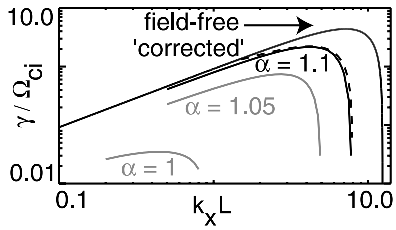

Figure 1. Linear growth curve (log-log plot) of anisotropic tearing for α = 1.0,1.05, and 1.1 from the nonlocal linear Vlasov code. Also shown are the analytical growth curves of anisotropic tearing (dashed) (equation (2)) and Weibel (field-free) instabilities for α = 1.1. See color version of this figure in the HTML.

Here $\varepsilon_e = \rho_e/L$, K_n is the modified Bessel function of the second kind, and $a_{\|e}$ is the parallel thermal velocity. The bracketed term in the definition for ν is the field-free dispersion relation; that is $\nu = 0$ recovers the Wiebel mode. The right hand side is the correction owing to the sheet pinch. This expression clearly establishes the morphing of tearing and Weibel modes into one mode, the so-called anisotropic tearing mode. There are two drivers, one is the anisotropy and the other is the current. The effect of having these two energy sources is that the resulting growth curve is somewhere between isotropic tearing and Weibel (field-free limit). To see this, we show in Figure 1 the linear growth rate of the tearing mode as computed from an exact nonlocal linear Vlasov code (Karimabadi et al., manuscript in preparation, 2004) for three values of electron anisotropy α = 1.0, 1.05, and 1.1 (solid curves). The other parameters in Figure 1 are $\rho_i/L = 1$, $m_i/m_e = 1836$, the ratio of electron plasma to gyrofrequency $\omega_{pe}/\Omega_{ce} = 4$, and $T_i/T_{\perp e} = 5$. Also shown are growth curves of the Weibel instability (left hand side of equation (2) set to zero) as well as the solution to equation (2) for α = 1.1 (dashed). The small differences between the linear code and solution to equation (2) are due to the approximations necessary in the analytical calculations. A number of points are immediately obvious from Figure 1. First, since Weibel growth extends to $k_xL > 1$ anisotropic tearing has assumed finite growth at short wavelengths beyond the isotropic tearing limit of $k_xL = 1$. Second, since Weibel growth rate is much larger than isotropic tearing for all k_x, anisotropic tearing has much larger growth rate than isotropic tearing. Finally, the growth curve of anisotropic tearing is lower than the Weibel as coupling to the tearing acts as a stabilizing term at short wavelengths. Similarly at oblique angles, tearing couples to the oblique Weibel mode resulting in large growth rates even at propagation angles as large as 45° (not shown) whereas the isotropic tearing has a smaller range of ~20°.

[4] Next we consider the opposite limit of $\alpha < 1$. Aside from the tearing mode, there are at least two other instabilities that have been discussed in the literature [e.g., *Laval and Pellat*, 1968; *Coppi and Rosenbluth*, 1968]. One is the electron fire-hose instability and the other is the current aligned Weibel instability. We do not consider the fire-hose mode here due to its larger instability threshold. *Laval and Pellat* [1968] derived the condition for instability of the current aligned Weibel as $(1 - \alpha) > (\rho_e/L)^2$ with a growth rate $\gamma/\Omega_{ce} = (1 - \alpha)^{5/4}$. Comparing this instability condition with equation (1), it is clear that this mode would set in

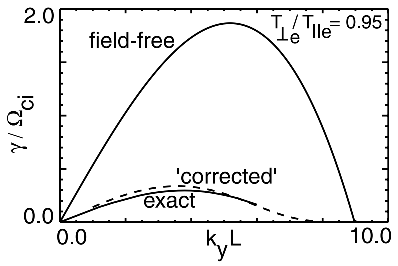

Figure 2. Linear growth curve of Weibel instability for the same parameters as in Figure 1 except α = 0.95. See color version of this figure in the HTML.

before the tearing stability condition (1) could be reached and would imply very large growth rates ($\gamma \gg \Omega_{ci}$) even for minute anisotropies. Since little is known about the properties of this instability in a neutral sheet, we have derived analytical expressions for its growth rate and compared with the linear Vlasov code. The results are shown in Figure 2. The parameters are the same as in Figure 1 except α = 0.95. Since the Weibel mode has maximum growth in the direction of minimum temperature, in the case α < 1 the mode has peak growth in the direction of the current with a small spread in angles. This mode is seen to have a large growth rate although it is much smaller than that based on *Laval and Pellat*'s [1968] expression ($\sim$43 Ω_{ci}). As in the α > 1 limit, the parallel Weibel mode is closely connected to the tearing mode but unlike that limit, here anisotropy results in reduction of growth rates of anisotropic tearing as well as the width of the unstable spectrum. This is because parallel Weibel with α < 1 is damped at parallel propagation, so when it couples to tearing it leads to damping rather than growth enhancement and when condition (1) is satisfied, anisotropic tearing becomes stabilized.

[5] We have verified our linear theory results by means of a full particle simulation as shown in Figure 3. The parameters are ρ_i/L = 1, m_i/m_e = 100, ω_{pe}/Ω_{ce} = 3, $T_i/T_{\perp e}$ = 1, and α = 0.8. In order to minimize the effect of the LHDI, we have included a uniform, isotropic background population with a 5% density compared to the peak density of the equilibrium population. The simulation box is 98.7 c/ω_{pe} in each direction with 448 $\times$ 448 cells and 24 million particles per species. The box size was chosen so that the fastest growing mode is the M = 4 with k_yL = 1.8.

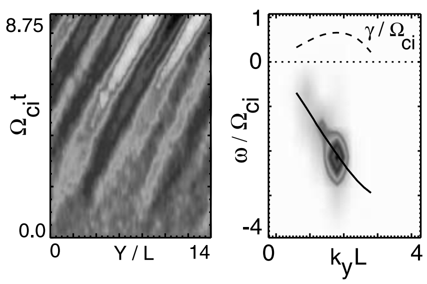

Figure 3. Simulation of current aligned Weibel mode in a current sheet with α = 0.8. Left: Contour plot of A_x in the y-t plane taken at Z = 0. Right: FFT (power) of A_x. Also shown are the dispersion curve (solid) and growth rate vs k_y (dashed) from linear Vlasov theory. See color version of this figure in the HTML.

Figure 3 (left) shows the wave fronts resulting from the current aligned Weibel instability during the linear stage. The maximum growth rate and the dispersion of the observed mode (right panel in Figure 3) are in very good agreement with the prediction obtained from the linear Vlasov code.

3. Nonlinear Evolution of Tearing Mode

[6] In order to address the saturation mechanism of single mode tearing, we have performed several 2D simulations. Due to space limitations, we discuss one representative case with simulation parameters ρ_i/L = 1, m_i/m_e = 100, ω_{pe}/Ω_{ce} = 5, $T_i/T_{\perp e}$ = 1, and α = 1. The simulation box was chosen to permit one linearly unstable mode with k_xL = 0.5. The initial evolution shown in Figure 4a is in good agreement with the predicted linear growth rate, followed by a slow march towards saturation. The final island width is near $\sim$0.26L, which is smaller than the singular layer thickness of $\sim$0.45L. As shown in Figure 4b, the saturation is well correlated with the electron anisotropy. In a 3D simulation, the current aligned Weibel instability would have a growth rate of $\gamma \approx$ 0.035Ω_{ci} for the anisotropy $\alpha \approx$ 0.95 at saturation, but this mode cannot exist in this 2D simulation. Instead, we have mimicked the effect of the Weibel instability by artificially isotropizing the electrons at saturation. Then we see in Figure 4a that the M = 1 tearing mode starts to grow again and saturates again at 0.38L near the singular layer thickness.

[7] From these and other simulations, including one with realistic mass ratio, we have developed the following picture. There are two competing processes for single island saturation. One is due to the trapping of electrons which yields saturation amplitude near the singular layer thickness. The other is the preferential parallel electron heating until marginal stability is reached. For realistic parameters, the latter is the dominant mechanism and the current aligned Weibel instability can at most increase the saturation amplitude to the singular layer thickness. However, the LHDI, if present, has a more substantial effect on the tearing mode because it preferentially heats the electrons in the

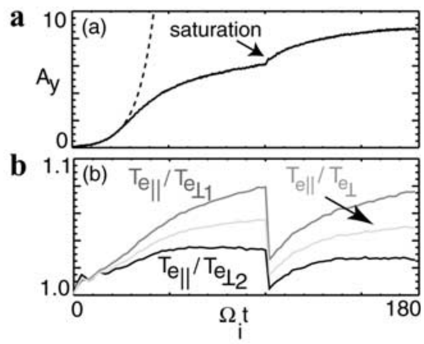

Figure 4. Simulation of single mode tearing with m_i/m_e = 100. Time evolution of (a) M = 1 mode amplitude and (b) electron anisotropy. The dashed line in (a) is the predicted linear growth γ = 0.11Ω_{ci} and the solid line is the simulation. The red and black lines in (b) show the anisotropy computed from the two perpendicular directions while the green curves shows the average. At saturation $t\Omega_{ci}$ = 100, the electron distribution is artificially isotropized and the simulation is allowed to proceed.

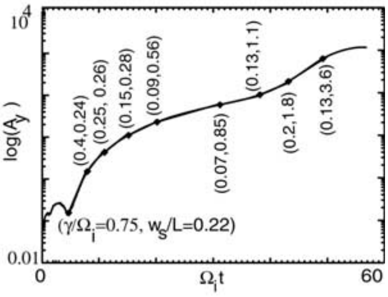

Figure 5. Simulation of multi-mode anisotropic current sheet with α = 1.5. Shown in parentheses are the growth rate and island amplitude.

perpendicular direction (Daughton et al., submitted manuscript, 2004) on a faster time scale than tearing can heat the electrons in the parallel direction. We have considered the saturation of single island tearing in the presence of $\alpha > 1$ but found that similar to the isotropic case, tearing saturates at below the singular layer thickness. This is because the shorter wavelength modes are more sensitive to changes in anisotropy. However, the presence of $\alpha > 1$ extends the spectrum to much shorter wavelengths, thus allowing multiple modes to interact [*Ricci et al.*, 2004]. Multiple unstable modes can also exist in the isotropic limit, but for a given system size, the presence of $\alpha > 1$ increases the number of unstable modes and significantly enhances their growth rate.

[8] The natural question is whether the presence of multiple unstable modes can get tearing past the small saturation amplitude seen in Figure 4. We show in Figure 5 the time evolution of the M = 1 mode for a simulation where there are 8 unstable modes in the system. Simulation parameters are $\rho_i/L = 1$, $m_i/m_e = 100$, $\omega_{pe}/\Omega_{ce} = 5$, $T_i/T_{\perp e} = 1$, and $\alpha = 1.5$. The simulation consisted of 1280 × 1536 cells with cell size of $0.13c/\omega_{pe}$ in each direction and 250 million particles per species and included a 20% background. Marked along side the growth curve in Figure 5 are the island widths at several points in time. It is clear that here the island amplitude has grown beyond the singular layer thickness and continues to grow beyond L as needed to achieve significant reconnection. The essential physics is that the longer wavelengths are less susceptible to a decrease in electron anisotropy. For example, mode k_xL = 0.5 is still unstable when the anisotropy is changed from α = 1.1 to 1 whereas mode k_xL = 1.5 is damped for anisotropy of α = 1. The single mode anisotropic tearing saturates due to reduction in α and it saturates before electrons are fully isotropized. In the presence of several unstable modes, however, as the anisotropy decreases the system coalesces to longer wavelengths which are still unstable. This allows the system to divert energy to the longest mode in the system and avoid the stabilization of the single mode case.

4. Conclusion

[9] Single mode tearing in a neutral sheet saturates at small amplitude and will not lead to significant reconnection. We considered the effect of electron anisotropy and multiple modes on this result and found that: (1) For $\alpha > 1$, the dominant instability within the neutral sheet that reduces the electron anisotropy is the anisotropic tearing mode. In the case of $\alpha < 1$, the current aligned Weibel instability may help isotropize the electrons, but this can at most increase the saturation amplitude of single island tearing to the singular layer thickness. (2) Even small levels of electron anisotropy $\alpha \sim 1.1$ lead to almost two orders of magnitude increase in the tearing growth rate and push the unstable spectrum to very short wavelengths. (3) A single tearing mode saturates at a small amplitude even in the presence of anisotropy. However, since anisotropy pushes tearing to such short wavelengths, there will be many unstable modes present. The system in this case evolves to much larger amplitudes and reaches ion scales as required to obtain significant reconnection. Based on these results we are led to the following picture of reconnection onset. The LHDI generates electron anisotropy $\alpha \sim 1.1$ within the current layer on a time scale much shorter than the growth time of isotropic tearing [*Ricci et al.*, 2004; Daughton et al., submitted manuscript, 2004]. This in turn drives the anisotropic tearing mode which has unstable modes extending to wavelengths a factor of 7 shorter than isotropic tearing. The presence of so many unstable modes and the fact that the longer modes are less susceptible to changes in α enable the system to coalesce to longer wavelengths, and bypass the single mode stabilization. We emphasize that even in the absence of anisotropy, we have verified that multi-mode tearing will get past the single mode saturation, however, the process will be slower. So the real impact of LHDI on reconnection is not through anomalous resistivity but through its effect on tearing.

[10] **Acknowledgments.** This work was supported by the UCSD's NASA SEC Theory Program NAG5-11754, NASA grant NAG5-11824, NSF grant ATM-9901665, Los Alamos National Laboratory LDRD program and IGPP grant. Simulations were performed on computers at the San Diego Supercomputer Center, which is supported by the National Science Foundation.

References

Biskamp, D., R. Z. Sagdeev, and K. Schindler (1970), Nonlinear evolution of the tearing instability in the geomagnetic tail, *Cosmic Electrodyn.*, *1*, 297.
Burkhart, G. R., and J. Chen (1989), Collisionless tearing instability of a bi-Maxwellian neutral sheet: An integrodifferential treatment with exact particle orbits, *Phys. Fluids B*, *1*, 1578.
Coppi, B., and M. N. Rosenbluth (1968), Model for the Earth's magnetic tail, in *Proceedings of the ESRIN Study Group*, edited by K. Schindler, p. 1, Eur. Space Res. Org., Neuilly-sur-Seine, France.
Forslund, D. W. (1968), A model of the plasma sheet in the Earth's magnetosphere, Ph.D. thesis, Princeton Univ., Princeton, N. J.
Galeev, A. A., F. V. Coroniti, and M. Ashour-Abdalla (1978), Explosive tearing mode reconnection in magnetospheric tail, *Geophys. Res. Lett.*, *5*, 707.
Gary, S. P. (1993), *Theory of Space Plasma Microinstabilities*, Cambridge Univ. Press, New York.
Gosling, J. T., M. F. Thomsen, S. J. Bame, and C. T. Russell (1989), Suprathermal electrons at Earth's bow shock, *J. Geophys. Res.*, *94*, 10,011.
Laval, G., and R. Pellat (1968), Stability of the plane neutral sheet for oblique propagation and anisotropic temperature, in *Proceedings of the ESRIN Study Group*, edited by K. Schindler, p. 5, Eur. Space Res. Org., Neuilly-sur-Seine, France.
Ricci, P., J. U. Brackbill, W. Daughton, and G. Lapenta (2004), Influence of the lower hybrid drift instability on the onset of magnetic reconnection, *Phys. Plamas*, in press.
Weibel, E. S. (1959), Spontaneously growing transverse waves in a plasma due to an anisotropic velocity distribution, *Phys. Rev. Lett.*, *2*, 83.

W. Daughton, Los Alamos National Laboratory, Los Alamos, NM, USA.
H. Karimabadi and K. B. Quest, Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093-0407, USA. (homa@ece.ucsd.edu)