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# <sup>1</sup> **New Insights into Dissipation in the Electron Layer** <sup>2</sup> **During Magnetic Reconnection**

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3 Detailed comparisons are reported between laboratory observations of electron-  
4 scale dissipation layers near a reconnecting X-line and direct two-dimensional  
5 full-particle simulations. Many experimental features of the electron layers,  
6 such as insensitivity to the ion mass, are reproduced by the simulations; the  
7 layer thickness, however, is about 3 – 5 times larger than the predictions.  
8 Consequently, the leading candidate 2D mechanism based on collisionless elec-  
9 tron nongyrotropic pressure is insufficient to explain the observed reconec-  
10 tion rates. These results suggest that, in addition to the residual collisions,  
11 3D effects play an important role in electron-scale dissipation during fast re-  
12 connection.

13 Despite the disruptive influences of magnetic reconnection on large-scale structures in  
14 plasmas, the crucial topological changes and their associated dissipation take place only  
15 within thin current layers. The classical collisional models, where electrons and ions flow  
16 together through a single thin and long layer, fail to explain the observed fast reconnection  
17 rates. Modern collisionless models predict [*Sonnerup*, 1979; *Mandt et al.*, 1994; *Birn*  
18 *et al.*, 2001] that ions exhaust through a thick, ion-scale layer while mobile electrons  
19 flow through a thin, electron-scale layer, allowing for efficient release of magnetic energy.  
20 These ion layers have been frequently detected in space [e.g. *Deng and Matsumoto*, 2001;  
21 *Øieroset et al.*, 2001; *Mozer et al.*, 2002] and studied in detail in the laboratory [*Ren*  
22 *et al.*, 2005; *Yamada et al.*, 2006; *Brown et al.*, 2006]. In contrast, the electron layers,  
23 where magnetic field dissipates, are rarely encountered in space and are often detected at  
24 places far from the reconnection X-line line [*Scudder et al.*, 2002; *Mozer*, 2005; *Wygant*  
25 *et al.*, 2005; *Phan et al.*, 2007]. Therefore, whether the electron layers indeed exist near  
26 the X-line, and if yes, whether their associated dissipation results predominantly from  
27 laminar two-dimensional (2D) or three-dimensional (3D) dynamics as suggested by *Xiao*  
28 *et al.* [2006, 2007], is still an open question. Here we report detailed comparisons between  
29 recent laboratory observations of the electron layers near the X-line [*Ren et al.*, 2008]  
30 and direct full-particle simulations in 2D. The measured electron layers display properties  
31 strikingly similar to predictions by 2D particle simulations, including their geometrical  
32 shape, insensitivity to ion mass, and sensitivity to the boundary conditions, but disagree  
33 on the electron layer thickness. As a consequence, the leading 2D mechanism based on  
34 collisionless electron nongyrotropic pressure is shown to be largely insufficient to explain

the observed reconnection rates. These results suggest that, in addition to the residual Coulomb collisions, 3D effects play an important role in electron-scale dissipation during fast reconnection.

The laboratory measurements were performed on the well controlled and diagnosed experiment, Magnetic Reconnection Experiment (MRX) [Yamada *et al.*, 1997], as illustrated in Fig.1. A pair of coil assemblies, known as flux-cores, are used to axisymmetrically initiate and maintain the reconnection process. Plasma is made by ionizing a pre-filled gas through pulsing toroidal field coil current within the flux-cores during the period when the current flowing in the poloidal field (PF) coils peaks. When the PF coil current is ramped down after the plasma is made, the field lines wrapped around both flux-cores are “pulled” back, reconnect, and move towards the flux-cores. Most of the important quantities can be either directly determined or indirectly inferred from these measurements in cylindrical coordinates  $(R, Z, \theta)$  assuming axisymmetry: poloidal flux  $\psi(R, Z, t) = \int_0^R 2\pi R' B_Z(R', Z, t) dR'$  where  $B_Z$  is the reconnecting field; the toroidal reconnection electric field  $E_\theta = (\partial\psi/\partial t)/2\pi R$ ; and the toroidal current density  $j_\theta \approx \mu_0^{-1} \partial B_Z / \partial R$ . The density  $n$  and electron temperature  $T_e$  are measured by a triple Langmuir probe and the flow speeds are determined by a Mach probe. The typical plasma parameters are:  $n \simeq (0.1 - 2) \times 10^{20} \text{ m}^{-3}$ ,  $T_e \sim T_i \simeq (3 - 15) \text{ eV}$ ,  $B < 0.5 \text{ kG}$ .

Detection of the electron dissipation layer is made possible by taking advantage of the differential motions between electrons and ions or the so-called Hall effects [Sonnerup, 1979] in the reconnection region without a guide field. These differential motions (or electric current) within the reconnection plane produce out-of-plane magnetic field component

57 ( $B_\theta$ ) with a quadrupole shape. Conversely, accurate measurements of the  $B_\theta$  profile can  
 58 determine the in-plane electron flow because of the much slower ion flow in this region,  
 59 and thus characterize the electron dissipation layer. These measurements are performed  
 60 using five linear arrays of pickup coils (Fig.1); each array measures a one-dimensional  
 61 profile of  $B_\theta$  with a frequency response of 300kHz and with spatial resolutions up to 2.5  
 62 mm. This distance is close to the electron skin depth,  $c/\omega_{pe}$  ( $=0.7-1.5\text{mm}$ ) where  $\omega_{pe}$  is  
 63 the electron plasma angular frequency, and adequately resolves the electron layer whose  
 64 minimum full thickness is 10 mm (see below). These arrays are housed by thin glass  
 65 tubes of outer diameter of 4 mm (four arrays) or 5 mm (one array) with shielding from  
 66 electrostatic noise. The presence of these probes in the plasma does not appear to affect  
 67 the reconnection process, but it may cause modest overestimates of the electron layer  
 68 thickness (see below).

69 One such example measurement is shown in Fig.2(b) where the in-plane electron flow  
 70 ( $V_{eZ}$  and  $V_{eR}$ ) is shown as arrows while the normalized, out-of-plane magnetic field is  
 71 shown as color-coded contours in the left half of the reconnection plane. Electron outflow  
 72 speed,  $V_{eZ}$ , is also shown as functions of  $Z$  in Fig.2(c) (at the current sheet center) and  
 73  $R$  in Fig.2(a) (across the reconnection region at the location where  $V_{eZ}$  peaks). The  
 74 dimensions of the electron layer can be characterized by the half thickness  $\delta_e$  (the radial  
 75 distance during which  $V_{eZ}$  decreases by 60% from its peak value) and the half length  
 76  $L_e$  (the axial distance during which  $V_{eZ}$  increases from zero to its peak). We positively  
 77 identify this region as the electron dissipation layer because both its dimensions,  $\delta_e$  and  
 78  $L_e$ , are independent of ion mass, as shown in Fig.3 for  $\delta_e$ .

Dissipation in the electron layer is governed by the electron equation of motion,

$$m_e n \left( \frac{\partial}{\partial t} + \mathbf{V}_e \cdot \nabla \right) \mathbf{V}_e = -en(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) - \nabla \cdot \mathbf{P}_e + en\eta_{Spitzer}\mathbf{j}, \quad (1)$$

where  $m_e$  is electron mass,  $\mathbf{P}_e$  electron pressure tensor, and  $\eta_{Spitzer}$  the Spitzer resistivity due to Coulomb collisions with ions [Spitzer, 1962]. In the modern collisionless steady-state 2D models, the reconnection electric field,  $E_\theta$ , can be only possibly balanced by either the Hall term  $(\mathbf{V}_e \times \mathbf{B})_\theta \approx (\mathbf{j} \times \mathbf{B})_\theta/en$ , the inertia terms, or the electron pressure tensor term  $(\nabla \cdot \mathbf{P}_e)_\theta$ . While the Hall term is important in supporting  $E_\theta$  within the ion layer [Birn et al., 2001; Ren et al., 2005; Yamada et al., 2006], it diminishes within the electron layer especially near the X-line due to the vanishing  $\mathbf{B}$ . It has been shown in particle simulations [Cai and Lee, 1997; Hesse et al., 1999; Pritchett, 2001; Kuznetsova et al., 2001] that  $E_\theta$  is supported primarily by the electron pressure tensor term following earlier suggestions [Vasyliunas, 1975]. This mechanism has been since widely accepted as the leading candidate to provide the required dissipation within the electron layer. It is, however, extremely difficult to confirm this pressure anisotropy, directly or indirectly, by measurements in real plasmas [Scudder et al., 2002].

One of the predictions of these 2D particle simulations is that the half thickness of the electron layer,  $\delta_e$ , scales as  $(1 - 2)c/\omega_{pe}$  [Pritchett, 2001]. The measured  $\delta_e$  in MRX, however, scales as  $\sim 8c/\omega_{pe}$  (Fig.3). Current blockage due to the probes is estimated to lead to a 6 - 44% increase in the measured  $\delta_e$ , depending on the ratio of  $\delta_e$  to the glass tube radius. Applying these corrections leads to  $\delta_e = (5.5 - 7.5)c/\omega_{pe}$ . To better compare with the experiment, on the other hand, we have constructed a kinetic numerical model [Dorfman et al., 2008] using boundary conditions similar to the MRX based on

101 the existing NPIC 2D code [*Daughton et al.*, 2006]. A 75cm×150cm simulation box is  
102 used with conducting boundary conditions for fields and elastic reflection for particles  
103 at the walls. Two current carrying coils of radius 1.3 cm are contained within a larger  
104 concentric flux core of radius 9.4 cm. The flux cores are spaced 40 cm apart as in the  
105 experiment. The flux core surface is approximated as an insulating boundary; particles  
106 may be absorbed or reflected. Due to constraints on computation resources, the number  
107 of the Debye lengths per  $c/\omega_{pe}$  is limited compared to the experiment, but there is strong  
108 evidence that the reconnection rate and electron layer scalings are insensitive to this  
109 number as long as the initial plasma beta is fixed [*Dorfman et al.*, 2008]. As the current  
110 is ramped down according to a sinusoidal waveform modeled on the PF coil current of  
111 MRX and reconnection is driven, both ion and electron dissipation layers are formed.  
112 Simulation parameters are chosen such that the global reconnection rate and the current  
113 sheet thickness on the ion scale match the observations. An example run is shown in  
114 Fig.2(d-f) in the same format as in Fig.2(a-c), and most of the observed features, including  
115 geometrical shapes and out-of-plane magnetic component, are reproduced.

116 The quantitative agreement between experiment and simulation is, however, found for  
117 only the global ion dynamics but not the local electron dynamics. The experimentally  
118 observed independence of  $\delta_e$  and  $L_e$  on ion mass was reproduced as shown for  $\delta_e$  by the  
119 open squares in Fig.3 for a fixed but artificially heavy electron mass. The values of  $\delta_e$   
120 in units of  $c/w_{pe}$  (evaluated using a line-averaged density at  $Z = 0$ ), however, are much  
121 smaller in simulations than in experiments, as illustrated by an alternative ordinate in  
122 Fig.2(a) and (d). In Fig.3, a case at higher mass ratio (400) with a different electron mass

123 is also plotted along with simulations with a realistic hydrogen mass ratio but a smaller  
 124 simulation domain and open boundary conditions [*Daughton et al.*, 2006]. All of these  
 125 cases, including more recent simulations using different open boundary conditions [*Huang*  
 126 *and Ma*, 2008], confirm a linear relation of  $\delta_e = (1.5 - 2)c/\omega_{pe}$  which is about 3 - 5 times  
 127 thinner than the experiment. In contrast, the dependence of the length of the electron  
 128 layer ( $L_e$ ) on  $c/\omega_{pe}$  is less robust; it can change significantly when the reflection coefficient  
 129 parameter on the flux core surface is varied [*Dorfman et al.*, 2008] as expected from the  
 130 observed dependence of the reconnection process on boundary conditions [*Kuritsyn et al.*,  
 131 2007].

132 The fact that the observed electron layers are substantially thicker than the numerical  
 133 predictions implies different dissipation mechanisms operating between these two cases.  
 134 In fact, our collisionless simulation model does not include the residual collisions between  
 135 electrons and ions or neutrals. But in MRX only a fraction of  $E_\theta$  can be accounted  
 136 for by the classical resistivity,  $E_\eta \equiv \eta_{Spitzer} j_\theta$  (Fig.4). Collisions between electrons and  
 137 neutrals, and electron collisional viscous effects are also estimated to be unimportant in  
 138 these discharges with low fill pressure. The electron inertia terms,  $(m_e/e)[(V_{eR}\partial/\partial R) +$   
 139  $(V_{eZ}\partial/\partial Z)]V_{e\theta}$ , are estimated to be on the order of 1 V/m, which is negligibly small. Near  
 140 the X-line, the effects due to electron nongyrotropic pressure can be well approximated  
 141 by [*Hesse et al.*, 1999]

$$142 \quad E_{NG} \equiv - \left( \frac{\nabla \cdot \mathbf{P}_e}{en} \right)_\theta \approx \frac{1}{e} \frac{\partial V_{eZ}}{\partial Z} \sqrt{2m_e T_e}, \quad (2)$$

143 as also validated in our kinetic model. Direct evaluations of  $E_{NG}$  using the measured pro-  
 144 file,  $V_{eZ}(Z)$  as in Fig.2, gives values only a small fraction of  $E_\theta - E_\eta$  (Fig.4). This leaves

145 the majority of  $E_\theta$  still unexplained, and therefore there must exist additional dominant  
146 dissipation mechanisms. Because our kinetic model contains all possible collisionless ki-  
147 netic mechanisms operative in 2D, these dominant mechanisms must be 3D in character,  
148 including effects due to current sheet deformation or plasma turbulence through wave-  
149 particle interactions within the current sheet. The latter was indeed already suggested by  
150 the detection of electromagnetic fluctuations [*Ji et al.*, 2004] when dissipation increases  
151 at low collisionalities [*Ji et al.*, 1998]. This subject is also under intensive theoretical  
152 and numerical investigation, such as recently by *Moritaka et al.* [2007], in the search for  
153 mechanisms for fast reconnection. Lastly, we comment that these 3D effects, in addition  
154 to the residual collisions, may diffuse substantially the predicted two-scale structures seen  
155 in the profiles of the reconnecting magnetic field, which remain undetected thus far in the  
156 experiment.

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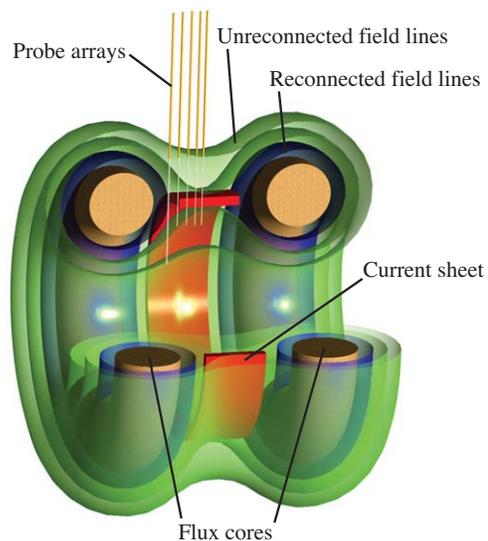
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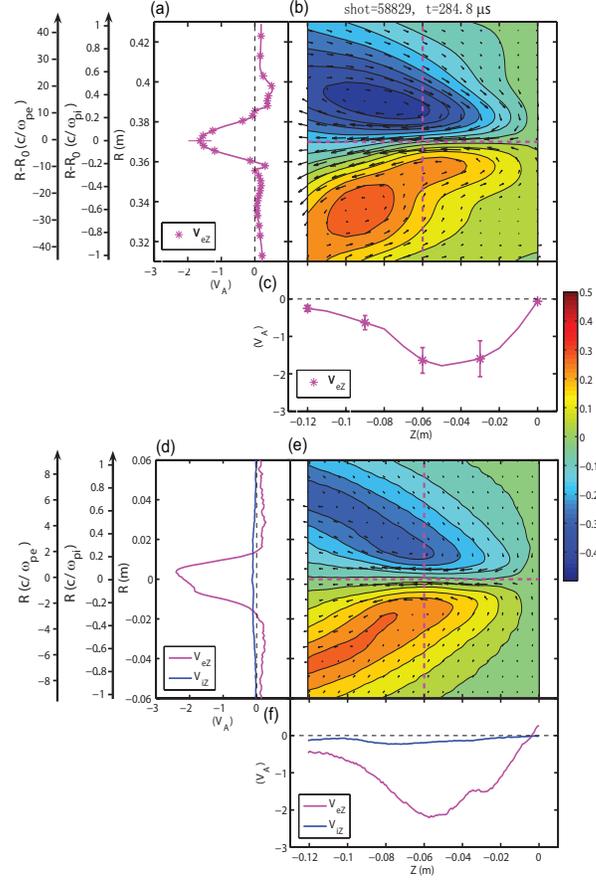
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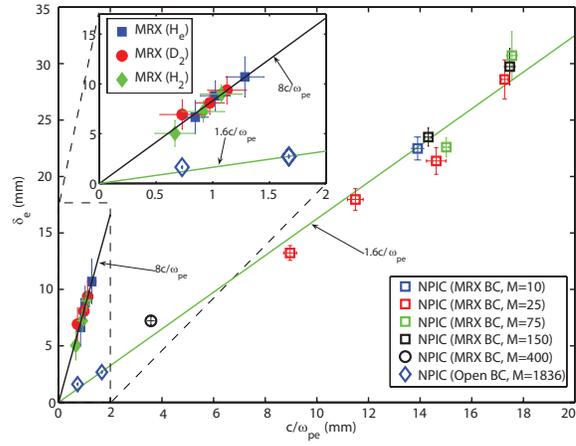
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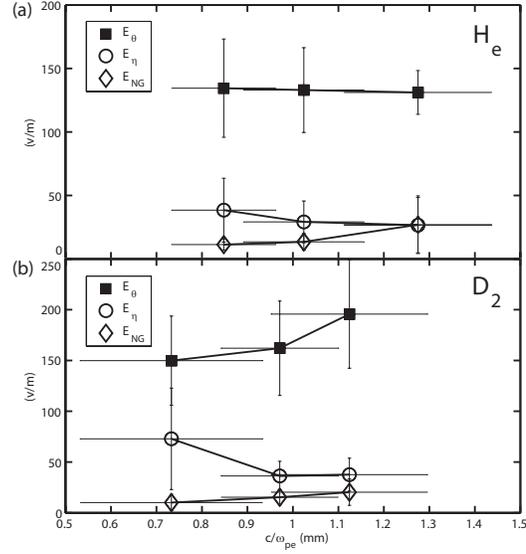
**Figure 1.** Experimental set-up of MRX device. The toroidal direction points along the current sheet while the poloidal direction wraps around the flux cores.



**Figure 2.** Identification of electron dissipation layer. The top three panels (a-c) show an experimental example taken from a hydrogen plasma with a fill pressure of 2 mTorr. Results from a corresponding simulation are shown in the same format in the lower three panels (d-f). The parameters used in the simulation are:  $864 \times 1728$  cells with 0.5 billion particles per species, initial density of  $2.6 \times 10^{19} \text{m}^{-3}$ ,  $m_i = m_{\text{hydrogen}}$ ,  $m_e = m_{\text{hydrogen}}/75$ , a time scale for the coil current ramp down is 185 initial ion cyclotron times, and no particle reflections at the flux core surface.



**Figure 3.** Scaling of width of electron dissipation layer. Filled symbols show the experimentally measured  $\delta_e$  as a function of the electron skin depth ( $c/\omega_{pe}$ ) for three different ion species. The error bars result mainly from shot-to-shot variations. Open symbols show  $\delta_e$  determined from 2D PIC simulations.



**Figure 4.** Composition of reconnecting electron field,  $E_\theta$ , for (a) helium and (b) deuterium plasmas. Total reconnecting electric field in MRX,  $E_\theta$ , and the part of it due to electron-ion collisions,  $E_\eta = \eta_{Spitzer} j_\theta$  near the X-line are plotted as a function of  $c/\omega_{pe}$ . The estimated electric field due to electron nongyrotropic pressure,  $E_{NG}$ , is also shown.

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