Experimental Verification of the Hall Effect during Magnetic Reconnection in a Laboratory Plasma

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In this Letter we report a clear and unambiguous observation of the out-of-plane quadrupole magnetic field suggested by numerical simulations in the reconnecting current sheet in the magnetic reconnection experiment. Measurements show that the Hall effect is large in the collisionless regime and becomes small as the collisionality increases, indicating that the Hall effect plays an important role in collisionless reconnection.

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Magnetic reconnection is the topological change of magnetic field by breaking and reconnecting magnetic field lines. It can happen in a region where the assumption of flux freezing in ideal magnetohydrodynamics (MHD) no longer holds. Magnetic reconnection converts magnetic energy to plasma kinetic energy by way of acceleration or heating of plasma particles and is considered to be a key process in the evolution of solar flares, in the dynamics of Earth's magnetosphere, and in the formation process of stars. It also occurs as an important self-organization processes in fusion plasmas, and it plays a key role in ion heating as well as in determining confinement properties of hot fusion plasmas. Motivated by the observations of solar flares, Sweet and Parker [1] proposed the first steady-state model of magnetic reconnection based on resistive MHD. However, in collisionless plasmas the reconnection rate of this model with classical Spitzer resistivity is too slow to explain solar flares and magnetic substorms. By including slow shocks, Petschek's model [2] can produce a faster reconnection rate, but with uniform resistivity this model has been found to be inadequate [3,4]. It is therefore necessary to go beyond resistive MHD physics to find fast reconnection mechanisms. Non-MHD effects are studied extensively in the magnetic reconnection experiment (MRX) [5] and other experimental devices [6,7].

In recent literature two mechanisms have often been cited for fast reconnection: anomalous resistivity generated by plasma turbulence [8] and the Hall effect of two-fluid MHD theory [9]. The first mechanism has been investigated experimentally and a positive correlation between resistivity enhancement and magnetic fluctuations has been found [10]. The second mechanism involves the decoupling of ion and electron flows in reconnecting current sheet in a laminar 2D fashion, thus generating the so-called Hall currents and out-of-plane quadrupole magnetic fields [9,11,12]. The reconnection rate is enhanced by the Hall effect [9,11]. As an important sign of the Hall effect and 2D laminar fast reconnection mechanism, the quadrupole magnetic field has been demonstrated to exist in many numerical simulations [11,13–15] and has been occasionally observed in the magnetosphere by some satellites [16–18]. This Letter reports a clear and unambiguous verification of this Hall effect in a laboratory plasma in the MRX by the identification of the out-of-plane quadrupole magnetic field during magnetic reconnection. The measurements provide a sufficiently unambiguous characterization of the quadrupole field to identify it with the quadrupole field of numerical simulations. Furthermore, the dependence of the quadrupole field amplitude on the collisionality indicates that the Hall effect plays an important role in collisionless reconnection. This discovery was made possible by the recent upgrade to the MRX facility, leading to a longer time duration of reconnection than in previous experiments.

In the MRX, the MHD criteria ($S \gg 1$, $\rho_i \ll L$, where S is the Lundquist number; ρ_i is the ion gyroradius; L is the system scale length) are satisfied in the bulk of the plasma [5]. Figure 1(a) shows a cross section of the MRX vacuum vessel in a R-Z plane and the positive toroidal direction

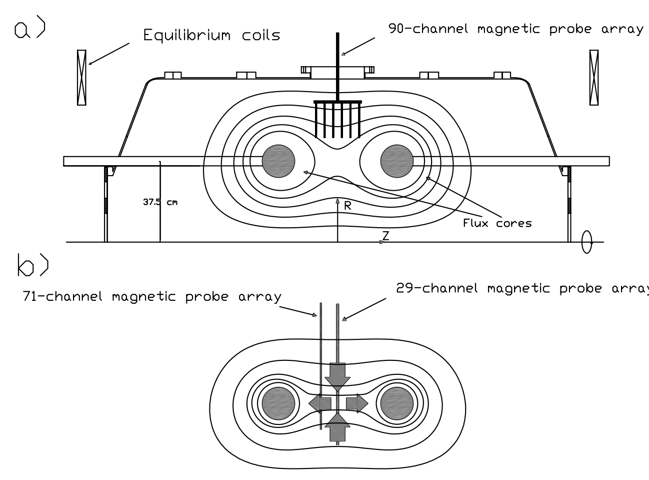

FIG. 1. (a) Cross-sectional view of the MRX vacuum vessel. (b) The positions of the 71-channel magnetic probe array and the 29-channel magnetic probe array.

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defined points into the plane. The overall initial geometry of the device is axisymmetric and thus global 2D geometry is ensured. In the MRX, two toroidal plasmas with annular cross sections are formed inductively around two flux cores (donut-shaped devices with poloidal and toroidal windings inside to generate poloidal magnetic field and plasma [5]). By simultaneously reducing the toroidal current in both flux cores, magnetic field lines are pulled towards the flux cores, forming a current sheet and inducing magnetic reconnection.

A variety of diagnostics are used in the MRX to measure essential parameters of the current sheet [19]. Three probe arrays were used extensively in the study of the Hall effect. As shown in Fig. 1(b), a 71-channel 1D magnetic probe array with spatial resolution of 1.25 mm ($\sim 0.04c/\omega_{\rm pi}$ in typical hydrogen discharges) was inserted radially at an off-center position at either $Z = 7$ cm or $Z = -7$ cm to measure the radial profile of the out-of-plane magnetic field in the toroidal direction as defined previously. The systematic error of the measurements by this probe is less than 10 G. A second, coarser 90-channel magnetic probe array was used to measure the three components of magnetic field (B_R, B_Z, B_T) at 30 locations in a R-Z plane simultaneously [Fig. 1(a)]. A third 29-channel 1D magnetic probe array with spatial resolution of 5 mm was put at the current sheet central plane ($Z = 0$ cm) to measure the reconnection magnetic field B_Z [Fig. 1(b)]. By fitting the measured reconnection field to the Harris sheet profile, the current density profile was calculated [19]. The experiments reported here were performed in both hydrogen and deuterium plasmas during "null-helicity" reconnection [5], where no net initial toroidal guide field B_T is applied.

In the present MRX plasma, a pull magnetic reconnection lasts for about 40 μs, much longer than the typical Alfvén time $\tau_A (= L/V_A \sim 1\ \mu\text{s})$ in the MRX plasmas. Only after magnetic reconnection starts is the out-of-plane quadrupole magnetic field observed. Using the 90-channel magnetic probe array, we measured the 2D profile of the out-of-plane quadrupole magnetic field. Figure 2 shows the contours of this out-of-plane quadrupole magnetic field in the diffusion region during magnetic reconnection, together with the vectors of the magnetic field in the R-Z plane. The spatial resolution of this figure is 4 cm in the Z direction and is improved to 1 cm in the R direction by scanning the probe radially and averaging several shots at each position. The quadrupole configuration of the out-of-plane magnetic field B_T can be clearly seen. The measured amplitude of this quadrupole magnetic field is of order 20–40 G. Two characteristic lengths for the out-of-plane toroidal magnetic field can be defined in this figure. $L_{\rm Hall}$ and $\delta_{\rm Hall}$ are defined as the distance between two peaks of the quadrupole magnetic field in the Z direction and in the R direction, respectively, and characterize the spatial scales of the quadrupole field in the Z direction and in the R direction. In Fig. 2, $L_{\rm Hall}$ is about 18–20 cm and $\delta_{\rm Hall}$ is about 5–6 cm. Taking a typical plasma density of 6×10^{13} cm^{-3} for these shots, we can calculate the ion skin depth for the deuterium plasma to be about 4 cm, so $L_{\rm Hall} \sim 5c/\omega_{\rm pi}$ and $\delta_{\rm Hall} \sim c/\omega_{\rm pi}$, which is consistent with numerical simulation ($L_{\rm Hall} \sim 5c/\omega_{\rm pi}$ and $\delta_{\rm Hall} \sim c/\omega_{\rm pi}$) [13].

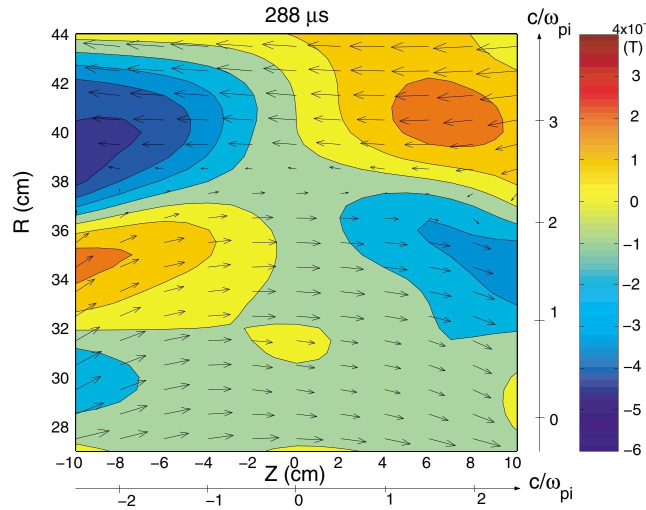

FIG. 2 (color). The magnetic field in the diffusion region for deuterium plasmas with fill pressure of 5 mT. $c/\omega_{\rm pi}$ is about 4 cm. The arrows show the measured magnetic field vectors in the R-Z plane. The size of the arrows is normalized to the maximum magnetic field strength in the R-Z plane, which is about 300 G. The color-coded contour plot shows the out-of-plane magnetic field B_T.

The radial profile of the quadrupole magnetic field can be measured by the 71-channel magnetic probe array with higher spatial resolution. Figure 3(a) shows a snapshot of the radial profiles of the out-of-plane toroidal magnetic field B_T at $Z = -7$ cm and the reconnection magnetic field B_Z and toroidal current density j_T at $Z = 0$ cm. Figure 3(b) shows the same profiles for another similar discharge where the out-of-plane toroidal magnetic field is measured at $Z = 7$ cm, the other side of the current sheet central plane. Both snapshots are taken at times well after magnetic reconnection starts. In both figures the toroidal magnetic field reverses sign at the current sheet center. For the $Z = -7$ cm case the toroidal field is positive at smaller radius and negative at larger radius. This polarity is reversed for the $Z = 7$ cm case, which reveals the quadrupole configuration of the out-of-plane toroidal magnetic field. The amplitude of the toroidal field ($B_{\rm Hall}$) in Fig. 3(a) is about 50 G, and in Fig. 3(b) it is about 60 G. (The smaller amplitude seen in Fig. 2 is likely because of the coarse spatial resolution of the 2D magnetic probe array.) For both cases the reconnection magnetic field B_Z has an amplitude of about 100 G. The ratio between the amplitude $B_{\rm Hall}$ and reconnection magnetic field B_{Z0} (at the shoulder) reaches 0.6, showing that a substantial amount of B_T can be gen-

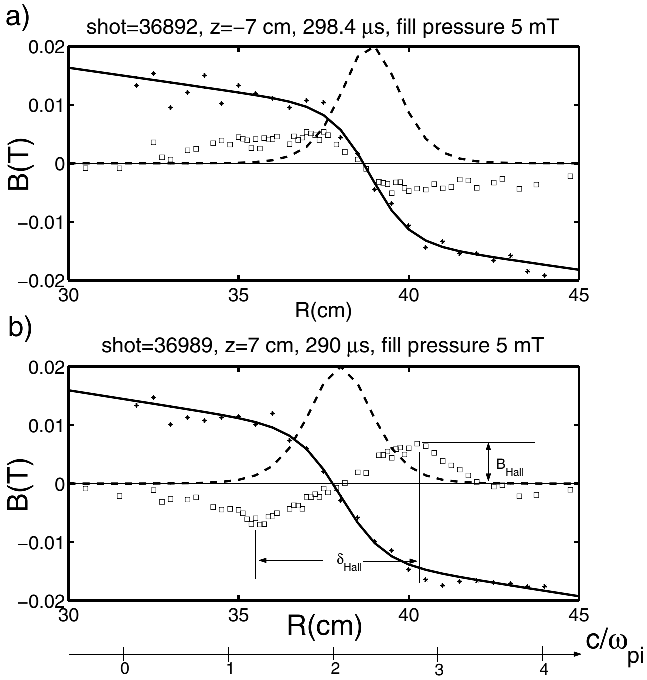

FIG. 3. (a) The radial profiles of the out-of-plane toroidal magnetic field B_T (open squares) at $Z = -7$ cm; and the 29-channel magnetic probe array data (asterisks) with the fitted reconnection magnetic field B_Z (solid line) and toroidal current density j_T (dashed line and not to scale) at $Z = 0$ cm. (b) Same as in (a) with the out-of-plane toroidal magnetic field measurement at $Z = 7$ cm. $c/\omega_{\rm pi}$ is about 3 cm for these hydrogen discharges.

erated during magnetic reconnection. This ratio is also in good agreement with the observation result of 0.55 in the magnetosphere [17]. In Fig. 3, $\delta_{\rm Hall}$ is about 3–5 cm, which is on the order of $c/\omega_{\rm pi}$ (typically 3 cm for these hydrogen discharges). The spatial scaling here is again consistent with numerical simulation [13]. The order of magnitude of the Z component of the in-plane Hall current density j_Z can be estimated based on this width. Using $j_Z \sim B_{\rm Hall}/(\mu_0 \delta_{\rm Hall}/2)$, the magnitude of j_Z is about $0.2\ {\rm MA/m^2}$ [Fig. 3(b)]. This in-plane current density is sizable compared to the reconnection current density ($\sim 0.7\ {\rm MA/m^2}$ in this case). Furthermore, the electron outflow velocity near the current sheet midplane ($R \sim 38$ cm) can be estimated based on the assumption that the current mostly comes from the electron flow. Using $v_{Ze} = j_Z/(en)$ and $n \sim 6 \times 10^{13}\ {\rm cm^{-3}}$, v_{Ze} is about 20 km/s comparable to $v_A \sim 30$ km/s based on the shoulder reconnection field and central density.

The experimental results reported here have shown that an out-of-plane quadrupole magnetic field is generated during magnetic reconnection. This self-generated magnetic field is the hallmark of the Hall effect thought to be important inside the diffusion region of magnetic reconnection [9]. The role played by the Hall effect in the force balance can be addressed by examining the generalized Ohm's law (neglecting the electron inertia term):

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{j} + \frac{\mathbf{j} \times \mathbf{B}}{en} - \frac{\nabla \cdot \mathbf{P}_e}{en}, \qquad (1)$$

where $\mathbf{j} \times \mathbf{B}/(en)$ is the so-called Hall term. The toroidal component of this equation shows how electric field is balanced by the Hall term and resistivity in the diffusion region. In order to see the importance of the Hall term, we evaluate $j_Z \times B_R/(en)$ and $j_R \times B_Z/(en)$. Using the experimental results reported above, we estimate these terms as follows. In Fig. 2 around the upstream area ($Z \sim 0$ and $R \sim 40$ cm) $j_R \sim B_{\rm Hall}/(\mu_0 L_{\rm Hall}/2)$, where $B_{\rm Hall}$ is the amplitude of the out-of-plane quadrupole magnetic field and $L_{\rm Hall}$ is the characteristic length defined previously. Because B_R is small in the same area, $j_Z \times B_R/(en)$ can be neglected. Taking $L_{\rm Hall} \sim 18$ cm and $B_{\rm Hall} \sim 40$ G, j_R is about $3.5 \times 10^4\ {\rm A/m^2}$. Using the typical upstream density of $3 \times 10^{13}\ {\rm cm^{-3}}$ and reconnection magnetic field B_Z of 200 G, $j_R \times B_Z/(en)$ is estimated to be about 140 V/m, which is sufficient to balance the typical reconnection electric field E_T of 100 V/m in the reconnecting current sheet in the MRX [10]. The reconnection electric field is calculated from $E_T = \dot{\Psi}/2\pi R$, where Ψ is the poloidal flux function obtained through $\Psi(R, Z) = 2\pi \int_0^R B_Z(R, Z) R dR$ (see Note 28 in [10] for more details). In the areas $Z \sim \pm 7$ cm and $R \sim 38$ cm, $j_Z \times B_R/(en)$ could be important. Since we do not have accurate measurements of B_R in the these areas, this question cannot be addressed now and is open for future research. We note that an investigation of the generalized Ohm's law has been reported by Cothran *et al.* [7], but the authors did not evaluate fully each vector component of the generalized Ohm's law in the paper. Instead, they just measure the absolute values. The large term they measured does not necessarily balance the reconnection electric field, because it included the $\mathbf{j} \times \mathbf{B}$ force due to just a neutral sheet current and they did not measure the direction and strength of the reconnection electric field.

Another important question is how the collisionality of the plasma affects the Hall effect. In Eq. (1) the term associated with collision effect is ηj, where η is the Spitzer resistivity. When collisionality is large, η is large and ηj can be more dominant in the generalized Ohm's law and the Hall term less important. It is crucial to investigate the transition from the collisional regime to the collisionless regime. By changing the fill pressure of working gas, we can change the plasma density thus the collisionality of the plasmas. In the MRX we denote the collisionality by the ratio $\delta/\lambda_{\rm mfp}$, where δ is the current sheet width and $\lambda_{\rm mfp}$ is the electron mean free path. Figure 4 shows the ratio between the quadrupole field amplitude $B_{\rm Hall}$ and the reconnection magnetic field B_{Z0} (at the shoulder of the diffusion region) as function of $\delta/\lambda_{\rm mfp}$. This ratio indicates the significance of the Hall effect during reconnection

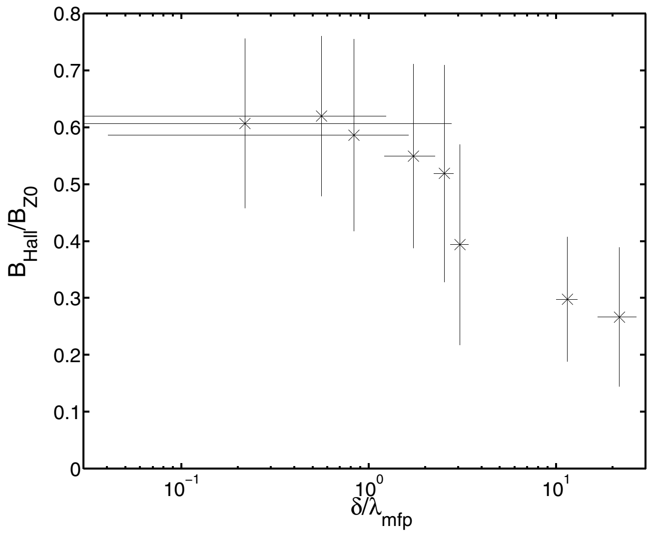

FIG. 4. Normalized amplitude of the out-of-plane quadrupole magnetic field versus the collisionality from a scan in fill pressure with deuterium. The error bars come from shot-to-shot variation.

processes. It can be seen that it changes from 0.6 to about 0.25 as $\delta/\lambda_{\rm mfp}$ increases from 0.2 to 20, i.e., the plasma changing from the collisionless regime to the collisional regime. This ratio correlates positively with the reconnection rate which is larger when the collisionality is smaller [20]. Although it is not straightforward to quantitatively calculate the dependence of $B_{\rm Hall}/B_{Z0}$ on $\delta/\lambda_{\rm mfp}$, this correlation supports the importance of the Hall effect in the collisionless reconnection processes [9]. A quantitative calculation of this dependence is in progress. A similar dependence on collisionality for magnetic fluctuations has been reported in a previous Letter [10]. The magnetic fluctuations have also been observed in the present experiments, and the relation between the quadrupole magnetic field and fluctuations is being investigated in the MRX. In addition, a bipolar electric field pointing to the center of the current sheet, predicted in numerical simulation [21] and observed in space observation [17], is also being studied in the MRX. The results will be reported in the future.

In conclusion, we have experimentally identified an out-of-plane quadrupole magnetic field during magnetic reconnection in the MRX. This quadrupole magnetic field is a confirmation of the Hall effect, which is essential to 2D laminar collisionless fast magnetic reconnection based on the two-fluid MHD model. We have verified experimentally that the Hall effect is large in collisionless plasmas and that it is sufficient to balance the reconnection electric field in the diffusion regime. This is the first clear and unambiguous identification of the Hall effect in the reconnecting current sheet of a laboratory plasma.

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