Low Frequency Magnetic Fluctuations during Magnetic Reconnection in Laboratory Experiment

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Large amplitude magnetic fluctuation with ion cyclotron range frequency was observed inside the current sheet region during magnetic reconnection in the plasma merging experiment for the first time. The fluctuation exhibited parallel phase velocity close to the drift velocity in the current sheet and parallel wavelength comparable with the ion gyroradius, suggesting that the reconnection rate enhancement is influenced by the drift kink instability of the current sheet.

Keywords: magnetic reconnection, plasma merging, anomalous resistivity, drift kink instability

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Magnetic reconnection plays important roles in a variety of magnetized plasmas, such as solar flares [1–3], the earth's magnetosphere [4], accretion disks [5], and laboratory plasmas [6–8]. One of the major questions on magnetic reconnection is "How does fast magnetic reconnection happen?". In the resistive magnetohydrodynamic (MHD) regime, the reconnection rate remains very small as compared with that of real reconnection events observed in the universe.

In numerical simulations [9, 10] and laboratory studies [6, 11], the enhancement of the reconnection rate has been reported when the length of the reconnection scale becomes shorter than the ion gyroradius (meandering radius) or inertia length. When the ions become unmagnetized, the two-fluid [12] effect or the ion kinetic behavior violates the MHD constraints and evokes microinstabilities in the diffusion region, increasing the effective resistivity to enhance the reconnection rate. One of the primary candidates for causing these microinstabilities is the lower-hybrid drift instability (LHDI) that has been observed in space [13] and in the laboratory [14]. Recent three-dimensional particle simulation studies have demonstrated that drift kink instability (DKI) [15] is triggered after the nonlinear saturation of the LHDI mode when the half-width of the current sheet drops below the ion gyroradius, resulting in the reconnection rate enhancement and anomalous ion heating [16, 17].

The TS-3 device [18] has been used to investigate the physical properties of magnetic reconnection by using a torus plasma merging method. They reported that fast magnetic reconnection is achieved when the current sheet half width is compressed shorter than the ion gyroradius [6] in conjunction with the anomalous resistivity and significant ion heating. However, the direct mechanism that enhances the reconnection speed still remains unclear. In the TS-3 device, two torus plasmas, with both poloidal and toroidal magnetic fields, are produced and their poloidal magnetic fields reconnect during the plasma merging process (co-helicity merging case [18]).

Figure 1 shows the two-dimensional magnetic field structure around the diffusion region at two different times (187 μs and 193 μs) observed by the magnetic probe array. The magnetic field lines (contour lines of poloidal magnetic flux Ψ with spacing of 0.3 mWb) are shown by solid lines together with the color-coded toroidal (out-of-plane) current density j_t. As shown in the figure, two initial torus plasmas approach each other along the axial (z) direction, and reconnection with current sheet occurs at around r = 180 mm. The reconnection outflow is accelerated ra-

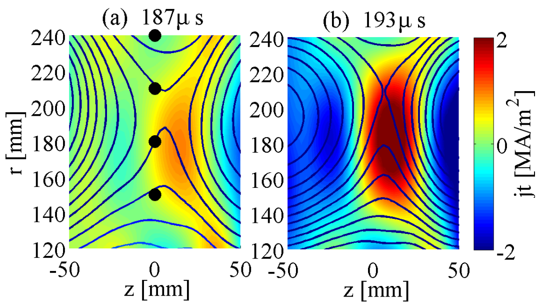

Fig. 1 Two-dimensional magnetic field structure around the diffusion region at (a) t = 187 μs and (b) t = 193 μs together with the toroidal (out-of-plane) current density shown by different colors. The black circles in (a) indicate the locations of magnetic fluctuation probes.

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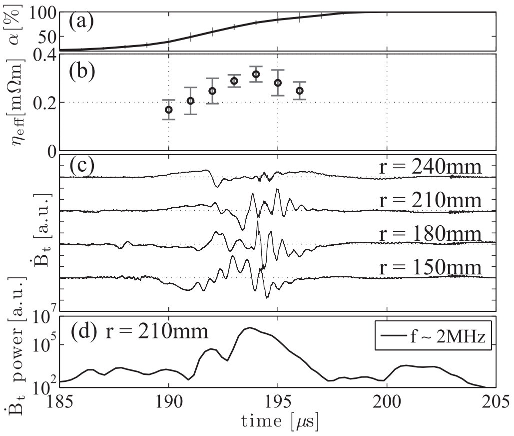

Fig. 2 Time evolutions of (a) common flux ratio α, (b) effective resistivity $\eta_{\rm eff}$ at the X-point, (c) magnetic fluctuation signals at four radial locations, and (d) magnetic fluctuation power of 2 MHz component.

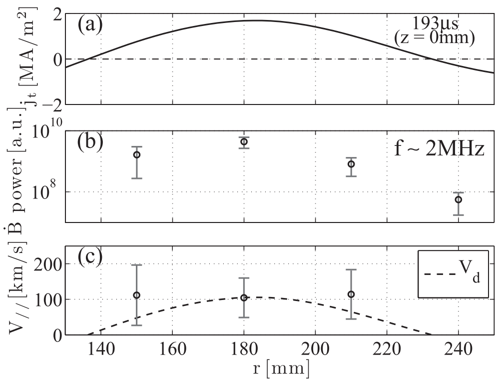

Fig. 3 Radial profiles of (a) toroidal current density on z = 0 mm, (b) magnetic fluctuations power with frequency $1.6 \leq f \leq 2.4$ MHz, and (c) toroidal phase velocity of the fluctuation (black circles) and the relative drift velocity (dashed line).

dially, in both inward and outward directions. The toroidal (out-of-plane) magnetic field $B_{\rm t}$, which serves as a guide field in the reconnection framework, is applied in this experiment by a center conductor current $I_z = 42$ kA. The guide field at the X-point $B_{\rm X}$ of 45 mT is about half as large as the reconnecting magnetic field $B_{//} = B_r$, that is approximately 80 mT. Typical ion and electron temperatures $T_{\rm i}$ and $T_{\rm e}$ are approximately 10 eV, and electron density $n_{\rm e}$ is 1×10^{20} m^{-3}. The ion gyroradius of $\rho_{\rm i} = 10$ mm and the ion inertia length of $c/\omega_{\rm pi} = 20$ mm are close to the half width of the current sheet $\delta \sim 20$ mm.

The magnetic fluctuation measurement was carried out by using two radial magnetic probe arrays which are separated by 4.5° in the toroidal angle. The probe locations are shown by black circles in Fig. 1 (a). Three pickup coils at each location were used to measure the magnetic fluctuations $\dot{B}_z = {\rm d}B_z/{\rm d}t$, $\dot{B}_r = {\rm d}B_r/{\rm d}t$, and $\dot{B}_{\rm t} = {\rm d}B_{\rm t}/{\rm d}t$.

Figure 2 (a) shows the time evolution of the common flux ratio $\alpha \equiv \Psi_{\rm com}/\min(\Psi_1, \Psi_2)$, where $\Psi_{\rm com}$ is the poloidal flux at the X-point and Ψ_1 and Ψ_2 are the poloidal fluxes of the two initial plasma toroids. Figure 2 (b) shows the effective resistivity $\eta_{\rm eff} = E_{\rm t}/j_{\rm t}$ evaluated at the X-point, where $E_{\rm t} = -(\partial\Psi_{\rm com}/\partial t)/2\pi r$. The plasma merging or magnetic reconnection continues from 185 up to 200 μs. Raw fluctuation signals $\dot{B}_{\rm t}$ measured at four radial locations are shown in Fig. 2 (c). Large amplitude magnetic fluctuations are observed during the magnetic reconnection inside the current sheet region (r = 150, 180, and 210 mm). The frequency spectrum of the fluctuation signal has clear peak at 2 MHz, which is about twice as high as the local ion gyro frequency. The magnetic field variation ΔB caused by the fluctuation is about 10 mT, which is larger than 10 % of the reconnecting magnetic field. Figure 2 (d) shows the evolution of the magnetic fluctuation power of the 2 MHz component measured at r = 210 mm. Large amplitude fluctuation appears from t = 191 to 195 μs, which is when the enhancement of effective resistivity is observed.

Figures 3 (a) and (b) show the radial profiles of the toroidal current density measured at t = 193 μs and total fluctuation power with frequency $1.6 \leq f \leq 2.4$ MHz. As shown, the fluctuation localizes inside the current sheet. Figure 3 (c) shows the parallel phase velocity of the fluctuation calculated from the phase difference between the two probes located 4.5° apart in the toroidal angle. The typical phase velocity along the magnetic field (toroidal direction) is about 100 km/s, which is close to the relative drift velocity $V_{\rm d} = j_{\rm t}/en_{\rm e}$ inside the current sheet (shown by the dashed line). The parallel wavelength of the fluctuation is about 50 mm, which is several times larger than the ion gyroradius.

In summary, we have detected magnetic fluctuations during magnetic reconnection with properties of (a) the ion cyclotron frequency range, (b) a wavelength comparable to the ion gyro scale, (c) a parallel velocity comparable to the relative drift velocity, and (d) a large amplitude that is up to 10 % of the reconnecting field. These properties are commonly observed in the DKI modes that have been discussed in the numerical studies. Our results suggest that the DKI mode may be responsible for the reconnection rate enhancement and the ion anomalous heating in the plasma merging experiment with a guide field.

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