Fast Reconnection in Low-density Hydrogen and Pair Plasmas

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Magnetic reconnection without a guide field in low-background-density plasmas has been studied by means of two-dimensional particle-in-cell simulations, and results in hydrogen and electron-positron (pair) plasmas have been compared. Reconnection is impulsive, and maximum reconnection rates of the order of one (measured in units of the Alfvén speed) have been observed in both types of plasmas when the background density in the Harris sheets is 1% of the current sheet density. This impulsive, strong reconnection electric field is important for particle acceleration. As the system evolves in time, the electron diffusion region extends in both inflow and outflow directions. Because of the broadening of the diffusion region, the aspect ratio of the diffusion region remains small, so that fast reconnection is sustained. In pair plasmas, the inertial term in the generalized Ohm's law becomes the most dominant term to balance the reconnection electric field before the maximum reconnection rate is attained, which contrasts with hydrogen plasmas where the most dominant term is the pressure tensor term.

Keywords: magnetic reconnection, particle-in-cell simulation, electron-positron plasma, particle acceleration, Hall effect

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1. Introduction

Magnetic reconnection is widely believed to play an important role in converting magnetic energy to particle energy during solar flares and substorms in the Earth's magnetosphere, which are dominated by hydrogen-like plasmas, and astrophysical objects such as pulsar winds and extragalactic jets, where electron-positron (pair) plasmas are thought to be the dominant plasma component [1–6]. During reconnection in hydrogen plasmas, ion motion is decoupled from electron motion in the diffusion region, and Hall currents are generated. Many simulation studies have demonstrated that fast reconnection is realized when Hall effects are included (for example, see [7]). The Harris sheet model is often used to study reconnection in such cases, and the magnetic field and density profiles are given as

$$B_x = B_0 \tanh(z/w), \quad (1)$$

$$n = n_0 \mathrm{sech}^2(z/w) + n_b, \quad (2)$$

where B_0 is the asymptotic magnetic field, w is the width of the current sheet, n_0 is the current sheet density, and n_b is the background density. Many numerical studies have used the background density n_b of the order of several 10% of n_0. For example, in the GEM reconnection challenge [7], where several different simulation codes were used to compare reconnection rates, $n_b = 0.2n_0$ was used, and reconnection rates of the order of 0.1 (in units of the Alfvén speed) were obtained when Hall effects are included. However, this background density, $0.2n_0$, is typically larger than realistic values in Earth's magnetotail region, where n_b can be less than $0.1n_0$ (observations show that a current sheet density ~ 0.1 to $1\ \mathrm{cm}^{-3}$ [8], and the lobe density ~ 0.01 to $0.1\ \mathrm{cm}^{-3}$ [9]). The Harris sheet model in low-background-density (low n_b) plasmas has been studied by few particle-in-cell (PIC) simulation studies. Pritchett (2001) studied reconnection with no background plasma ($n_b = 0$) [10], and obtained a maximum reconnection rate around 2. Fujimoto (2006) studied reconnection with $n_b \sim 0.04n_0$ [11], and obtained a maximum reconnection rate around 0.7. These reconnection rates are much larger than 0.1. Since there is great interest in the problem of fast reconnection in hydrogen plasmas, it is worth reflecting on why reconnection in the low-density regime is significantly faster, and what physical mechanisms are operative in this regime.

Reconnection in pair plasmas has also been a subject great attention in recent years. Unlike hydrogen plasmas there is no scale separation between electron and positron motion, therefore the Hall current cancels out exactly. Many studies have demonstrated that fast reconnection is realized in pair plasmas without the intervention of Hall effects [11–22]. Several studies use background densities of the order of several 10% of the current sheet density, and obtain reconnection rates that are of the order of 0.1 [18, 20]. On the other hand, if the background density becomes of the order of $0.01n_0$, larger reconnection rates are observed. In relativistic pair plasmas, PIC simulations with $n_b \sim 0.01n_0$ [12, 15, 17] showed that reconnection rates lie in the range $\sim 0.3 - 0.4$. A two-fluid simulation [22] with $n_b = 0.005n_0$ showed a reconnection rate of 0.6. In non-relativistic pair plasmas, we have re-

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cently demonstrated by PIC simulations that reconnection rates depend on the background density n_b, and reconnection rates become of the order of 1 when $n_b = 0.01n_0$ [23]. It has been demonstrated that before the reconnection rate becomes of the order of 1, when the reconnection electric field is increasing, the reconnection electric field is balanced dominantly by the inertial term in the generalized Ohm's law. Reconnection becomes fast because of the density decrease in the diffusion region, caused by particle acceleration away from the region. After the reconnection rate attains its maximum value, it decreases with time, but reconnection remains fast. As time elapses, the diffusion region is extended in the outflow direction, and it is also broadened in the inflow direction; therefore, the aspect ratio of the diffusion region is kept small so that a regime of fast reconnection is realized.

It is important to compare hydrogen plasmas (with Hall term) and pair plasmas (with no Hall term) in order to understand what makes reconnection fast. In this paper, we will study in detail fast reconnection in both types of plasmas with low background densities.

2. Simulation Results

We have carried out 2-dimensional PIC simulations to study reconnection without a guide field. In the Harris sheets, prescribed by Eqs. (1) and (2), we chose the background density $n_b = 0.01n_0$, and the width $w = d_{i0} = (4\pi n_0 e^2/m_i)^{1/2}$, where d_{i0} is the ion skin depth in a density n_0, e is the charge, and m_i is the ion mass. For a hydrogen plasma, the mass ratio $m_i/m_e = 25$, the temperature ratio $T_i/T_e = 5$, and the system size is $-102.4d_{i0} < x < 102.4d_{i0}$ and $-25.6d_{i0} < z < 25.6d_{i0}$. For a pair plasma, $m_i/m_e = 1$, $T_i/T_e = 1$, and the system size is $-204.8d_{i0} < x < 204.8d_{i0}$ and $-25.6d_{i0} < z < 25.6d_{i0}$. The Alfvén speed v_{A0} is equal to $B_0/(4\pi m_i n_0)^{1/2}$ for hydrogen plasmas, $B_0/(8\pi m_i n_0)^{1/2}$ for pair plasmas, and is chosen to be $0.05c$, where c is the speed of light. The conditions $B_0^2/8\pi = n_0(T_i + T_e)$, $|v_{di} - v_{de}| = (2c/weB_0)(T_i + T_e)$, and $v_{de}/v_{di} = -T_e/T_i$ are satisfied at $t = 0$, where v_{de} and v_{di} are drift velocities to the y direction of electrons and ions in the current sheet, respectively. The system is periodic in the x direction, and the z boundaries are conducting walls where particles are reflected. In the current sheet, about 2800 particles per cell for each species are used, and about 28 particles per cell in the background. In the pair plasma, 2048 (x direction) × 256 (z direction) grids are used, and d_{i0} spans 5 grids. In the hydrogen plasma, 2048 × 512 grids are used, and d_{i0} spans 10 grids, while d_{e0} (electron skin depth) spans 2 grids. As time evolves, the density in the reconnection region decreases, and both ion and electron skin depths become much larger than the initial d_{i0} and d_{e0}. A perturbation is added to the magnetic flux function as $\Psi_1 = aB_0 d_{i0}\mathrm{sech}^2(x/L)\mathrm{sech}^2(z/w)$, where we chose $a = 0.2$ and $L = 2w$.

Fig. 1 shows the time evolution of the reconnection

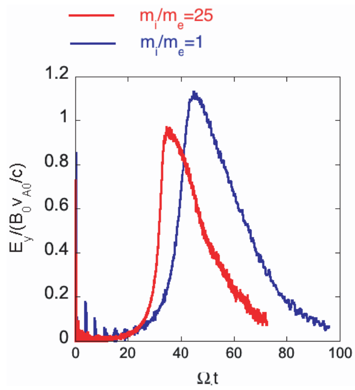

Fig. 1 Reconnection rates as a function of time

rate normalized by $B_0 v_{A0}/c$. Both curves (red: hydrogen plasma, blue: pair plasma) show that the reconnection process is impulsive. The maximum reconnection rates are of the order of 1, and these rates are much larger than that for the GEM reconnection challenge (∼ 0.1), where the same normalization $B_0 v_{A0}/c$ is used [7]. In our previous study for low-density pair plasmas [23], we demonstrated that the reconnection rate normalized by $B_d v_{out}/c$, where B_d is the magnetic field in the inflow edge of the diffusion region, v_{out} is the outflow speed, is also of the order of 1 when $n_b = 0.01n_0$. The result in Fig. 1 suggests that the maximum reconnection rates do not vary very much with the mass ratio, and fast reconnection does not depend on the presence of the Hall current. After the maximum values of the reconnection rate are attained in the impulsive phase, they decrease, and at the end of the simulations, both are of the order of 0.1. Reconnection is still fast in the late stage of reconnection, and we will discuss later the structure of diffusion region in this late stage of reconnection. We would like to emphasize that this impulsive phase with a reconnection rate of the order of 1 is important, not the least because significant particle acceleration occurs during this phase. Fig. 2 shows a phase space x-γ (γ is a Lorentz factor) for electrons in the hydrogen plasma. The upper panel is at the time of the maximum reconnection rate ($\Omega_i t = 34.3$), and the lower panel is after the maximum reconnection rate ($\Omega_i t = 54.2$). At the point of the maximum reconnection rate (upper panel), many electrons in the vicinity of the X-point ($x = 0$) are accelerated and those γ factors increase up to 2. As time elapses, those accelerated particles are expelled from the X-point and they move to the downstream region as outflows. The lower panel shows that there are two peaks of accelerated electrons around $x = -30d_{i0}$ and $x = 30d_{i0}$, where the electric field E_y peaks (see Fig. 3). The maximum γ at this time is around 5. Acceleration continues until the end of the simulation, and the maximum γ is around 10 at $\Omega_i t = 70$. This maximum γ observed in this low n_b simulation is much larger than that observed in simulations with higher n_b (for example, [24]). This is because of the maximum E_y that accelerates electrons in this low n_b sim-

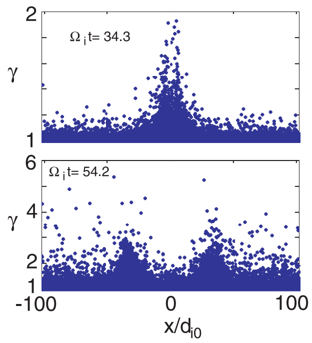

Fig. 2 Phase space x-γ for electrons in the hydrogen plasma

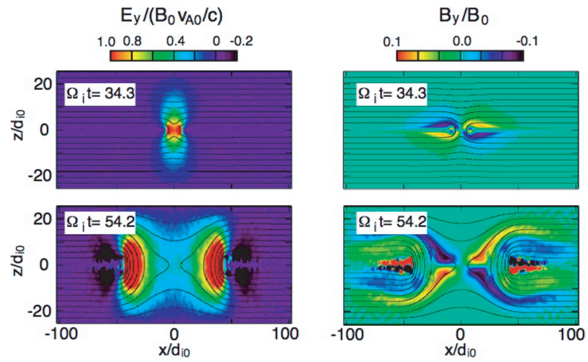

Fig. 3 Time evolutions of E_y and B_y

ulation is much larger than that in high n_b simulations.

Fig. 3 displays the time-history of the electric field E_y and the magnetic field B_y in the x-z plane for hydrogen plasma simulation. In these plots, color contours show the amplitudes of E_y and B_y, and the black curves are the magnetic field lines. The top panels correspond to the time of the maximum reconnection rate, and the bottom ones correspond to instants of time after the maximum reconnection rate is attained (at $\Omega_i t = 54.2$). At the instant of the maximum reconnection rate $\Omega_i t = 34.3$, E_y is localized in the vicinity of the X-line. As time evolves, the two peaks of E_y propagate in the x direction, and those peaks are localized around the boundaries of the magnetic island. The right panels show the quadrupolar structure of B_y along the magnetic separatrices. These plots show that the structure of electric and magnetic field in this impulsive reconnection phase is quite dynamic.

Fig. 4 compares the contours of electron fluid velocity v_{ey}, and roughly speaking, the areas surrounded by the solid rectangles represent the electron diffusion region. The top panels are at the time of the maximum reconnection rate, and the middle and bottom ones are at the late stage of reconnection after the maximum reconnection rate is realized. As time passes, the diffusion region is extended to both the outflow (x) and inflow (z) directions. At the end of the simulations (bottom panels), the half-lengths of the electron diffusion regions are around $50d_{i0}$ for the hydrogen plasma, and $70d_{i0}$ for the pair plasma. At

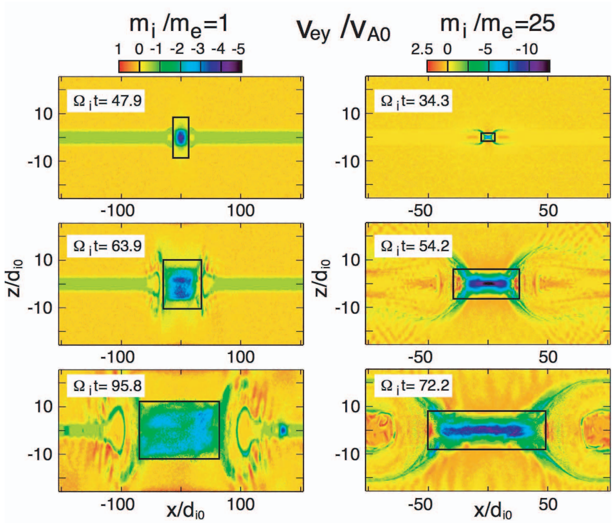

Fig. 4 Time evolutions of electron fluid velocity v_{ey}

the same time, the broadening of the diffusion region occurs. The half-widths of the electron diffusion regions are of the order of $10d_{i0}$ for both plasmas. The width $10d_{i0}$ corresponds to about $0.5d_i$ ($2.5d_e$ for the hydrogen plasma and $0.5d_e$ for the pair plasma) where d_i is based on a local density n at the center of the electron diffusion region. At the end of the simulations, the densities in both simulations are $n \sim 0.002n_0$ at the center of the electron diffusion region. The density decreases continuously with time, because particles are expelled from the X-point to the exhaust regions. Since the width of the electron diffusion region is proportional to the electron skin depth d_e, the width becomes larger as the density becomes smaller. Because of the broadening, the aspect ratio of the electron diffusion region remains at small values , around 6 in both simulations, so that fast reconnection is possible despite the extension of the electron diffusion region.

We have compared each term in the generalized Ohm's low in the z direction for the hydrogen as well as the pair plasma. The generalized Ohm's law is given by

$$E_y = -\frac{1}{c}(\boldsymbol{v} \times \boldsymbol{B})_y + \frac{1}{nec}(\boldsymbol{J} \times \boldsymbol{B})_y - \frac{1}{ne}\nabla \cdot \boldsymbol{P}_{ey} - \frac{m_e}{e}\left(\frac{\partial}{\partial t} + \boldsymbol{v}_e \cdot \nabla\right) v_{ey}, \quad (3)$$

for hydrogen plasmas, and

$$E_y = -\frac{1}{c}(\boldsymbol{v} \times \boldsymbol{B})_y - \frac{1}{ne}\nabla \cdot \boldsymbol{P}_{ey} - \frac{m_e}{e}\left(\frac{\partial}{\partial t} + \boldsymbol{v}_e \cdot \nabla\right) v_{ey}, \quad (4)$$

for pair plasmas. In Fig. 5, the green curves represent the term $-(m_e/e)(\partial v_{ey}/\partial t)$. It is seen that the green curve is the most dominant term in the pair plasma in the upper left panel (before the maximum reconnection rate), while the green curve is less important in the hydrogen plasma. In our previous study, we have shown that the increase of the

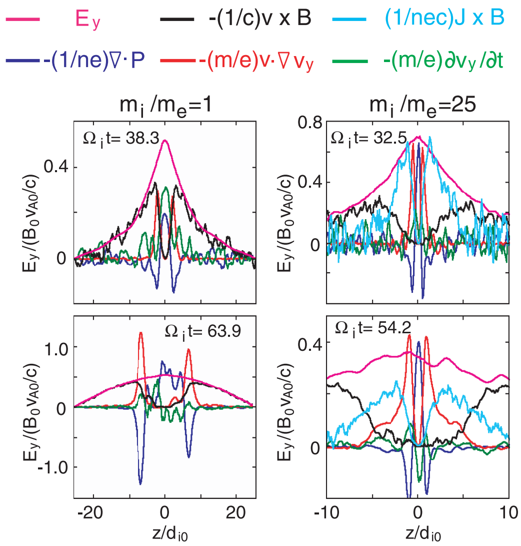

Fig. 5 Time evolutions of each term of the generalized Ohm's law

term $-(m_e/e)(\partial v_{ey}/\partial t)$ is because of particle acceleration and decrease of the density in the diffusion region [23]. Acceleration and density decrease also occur in the hydrogen plasma; however, the time scale of the acceleration is on the scale of ions, therefore, the time derivative of v_{ey} becomes smaller than that in the pair plasma. Instead of the inertial term, the pressure tensor term (the blue curve) is the most dominant term that balances the reconnection electric field for the hydrogen plasma. The importance of the pressure tensor at the X-line was discussed in [25], and our result in the top right panel is consistent with that study. The light blue curves are the Hall term, and in the top panel this term is large and balances the E_y field in the ion diffusion region (outside of the electron diffusion region where the blue and red curves are large). After the maximum reconnection rate for the hydrogen plasma (the right bottom panel), there is a reduction of the Hall term, and the red curve (the term of $-(m_e/e)\boldsymbol{v}_e \cdot \nabla v_{ey}$) increases in the vicinity of the edge of the electron diffusion region $(2 < |z/d_{i0}| < 5)$. Note that the region where the Hall term is reduced is near the region where the gyro-viscous cancelation between the ion inertial term and the ion pressure term is observed as in [25]. This suggests the importance of the kinetic effects in that region in the late stage, which require further exploration.

3. Summary

We have investigated magnetic reconnection in low-background-density plasmas in both hydrogen and pair plasmas by means of 2-dimensional particle-in-cell simulations. We have shown that reconnection rates in both plasmas become of the order of 1 when the background density is $n_b = 0.01n_0$, and the reconnection electric field is much larger than that in reconnection with higher n_b. After the reconnection rate becomes the maximum value, it decreases and the rate eventually becomes of the order of 0.1. This impulsive phase of large reconnection electric field is important for particle acceleration, and we have obtained strong electron acceleration in hydrogen plasmas. We have observed the extension of the electron diffusion region in the outflow direction and the broadening in the inflow direction. Reconnection in the late stage is fast because of the broadening of the diffusion region so that the aspect ratio of it is small. Before the maximum reconnection rate is attained in pair plasmas, the dominant term in the generalized Ohm's law that supports the reconnection electric field is the time derivative part of the inertial term, while in hydrogen plasmas that term is of much less importance. In hydrogen plasmas, the Hall effect decreases in the late stage of reconnection, and the inertial term becomes large near the edge of the electron diffusion region to compensate for the reduction of the Hall term.

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