Kinetics of Cold Ions in Asymmetric Reconnection: Particle-in-Cell Simulation

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Abstract: Cold ions from Earth's ionosphere and plasmasphere have frequently been observed at the magnetopause, where they impact reconnection and get energized in the process. The behavior of cold ions in different regions of magnetopause reconnection is not well understood. This study investigates their kinetics in asymmetric reconnection through a 2.5-D fully kinetic simulation. The simulation starts with cold ions being present only in the magnetosheath. We find that the velocity distribution functions (VDFs) of cold ions in different reconnection regions are composed of two types of particles, distinguished by their ability to penetrate the magnetosheath. One type produces ring-shaped distributions in the magnetosheath due to meandering motion, while the other generates ring-shaped distributions in the magnetospheric separatrix as a result of gyromotion. The reconnection electric field \(E_y\) has a negative effect on one type and a positive effect on the other. Moreover, the Hall electric field \(E_z\) can stepwise accelerate the meandering particles. The cold ion temperature increases significantly in the magnetosheath as compared to its original temperature, due to the enhancement of cold ions in the magnetosheath separatrix region. These findings further emphasize the necessity to examine the VDF for an all-round comprehension of the particle heating mechanism and contribute to a better understanding of cold ion dynamics at the Earth's magnetopause.

1. Introduction

Magnetic reconnection is a fundamental process in plasma physics that plays a crucial role in converting magnetic energy into plasma energy (Birn et al., 2001; Deng & Matsumoto, 2001; Dungey, 1961). During the reconnection process, anti-parallel magnetic field lines undergo a “disconnect” and “reconnect” at a specific point known as the X-line (e.g., Birn et al., 2001; Ji et al., 2022). The reconnected magnetic field lines accumulate and propagate downstream, leading to the formation of the flux pileup region (FPR) (e.g., Fu et al., 2011; Song et al., 2020). This process accelerates and heats the plasma, generating a reconnection outflow (Angelopoulos et al., 2013; Huang et al., 2015; Zhong et al., 2019).

Magnetic reconnection occurs in different regions of the Earth's magnetosphere, namely the magnetopause and magnetotail, where they exhibit asymmetric and symmetric reconnection, respectively (e.g., Argall et al., 2022; Burch et al., 2016; Lu et al., 2022; Zhou et al., 2016, 2009a, 2009b, 2011, 2019). Low-energy ions (in the range of several electron volts) originating from the plasmasphere or ionosphere can penetrate into these regions and influence the reconnection process (e.g., Engwall et al., 2009; Lee et al., 2016). The presence of cold ions can significantly alter the plasma density and Alfvén velocity, resulting in a reduction of the reconnection rate (Borovsky & Denton, 2006; Walsh et al., 2013). Moreover, cold ions can impact the Hall effect in reconnection (André et al., 2016; Toledo-Redondo et al., 2015), induce a new scale between the hot ion and electron scales, and generate the cold ion diffusion region (Divin et al., 2016).

During the reconnection process, cold ions can be heated or accelerated (e.g., Norgren et al., 2021; Song et al., 2022; Toledo-Redondo et al., 2017, 2016; Zhang et al., 2018). Toledo-Redondo et al. (2021, 2017, 2016) conducted comprehensive investigations using cluster and magnetospheric multiscale observations to examine the effects of asymmetric reconnection on cold ions in the dayside magnetopause. Their study reveals that waves in the separatrix region near the X-line can heat cold ions, with at least 10%–25% of the energy entering the ion being used for cold ion heating. Moreover, the temperature increase of cold ions during magnetopause reconnection was found to depend on their density. Dargent et al. (2019) conducted a fully kinetic simulation to investigate the velocity distribution functions (VDFs) and temperature anisotropy of cold ions in asymmetric reconnection.
Their study demonstrates that cold ions experience heating mainly in the parallel direction within the magnetospheric separatrix. The crescent-shaped signatures of cold ions appear when cold ions can cross the magnetospheric Hall electric field layer in less than one gyration and reach the side with few cold ions. Employing particle-in-cell (PIC) simulations, Song et al. (2023a) showed that the temperature of cold ions can increase by approximately 20 times compared to the initial cold ion temperature in both the outflow and the separatrix region of asymmetric reconnection.

Both observations and simulations have revealed that the cold ion temperature is enhanced during asymmetric reconnection. However, the temperature can be increased even in the absence of heating, for instance, the existence of multi cold beam may also give rise to a very high temperature, which is dubbed as “pseudothermal” in Goldman et al. (2020, 2021). Therefore, the observed temperature rise of cold ions may be a result of a kinetic effect rather than actual bulk heating. Here, we use the term “bulk heating” to describe the process in which discrete VDFs gradually aggregate into a single core over time. To ascertain whether the temperature enhancement is caused by bulk heating or not, a thorough investigation of the VDFs of cold ions is necessary. In this study, we investigate the formation of cold ion VDFs in different regions of asymmetric reconnection by tracing particle trajectories. By exploring the kinetics of cold ions, we aim to provide a deeper understanding of cold ion acceleration/heating in asymmetric magnetic reconnection and ultimately enhance our comprehension of the cold ion dynamics in the magnetosphere.

2. Simulation Setups

In this study, a 2.5-D PIC simulation is employed, which is two-dimensional in space and three-dimensional in velocity space. The simulation code, initial model, and parameters used are identical to those used in a previous study (Song et al., 2023a). To simulate cold ions originating from the plasmasphere, the cold ions are initially located on the magnetospheric side (Dargent et al., 2019, 2020, 2017). The cold ions have the same mass and charge as hot ions, with the ion mass set to 100 times the electron mass. The simulation domain is $50d_i \times 25d_i$, resolved by $2,000 \times 1,000$ cells, where $d_i$ is the ion inertial length based on the plasma density, $n_p$, on the magnetosheath side. The plasma $\beta$ on the magnetosheath side is $\beta_{sh} = 5$, where the subscript “sh” represents the magnetosheath. The ratio of the magnetic field strength is $B_{sp}/B_{sh} = 2$, where the subscript “sp” represents the magnetospheric side. The temperature ratio of hot ions to electrons is $T_{ih}/T_e = 5$, and the temperature ratio of hot ions to cold ions is $T_{ih}/T_{ic} = 100$, where the subscripts “ih”, “ic”, and “e” denote the hot ions, cold ions, and electrons, respectively. The density ratio of cold ions to hot ions on the magnetospheric side is $N_{ih}/N_{ih} = 10$. The reconnection is an asymmetric anti-parallel reconnection, and the guide field is zero. The simulation plane is the $X-Z$ plane, with the periodic boundary condition employed in the $x$-direction and the ideal conducting boundary condition used in the $z$-direction (Birn et al., 2001). When particles hit the conducting boundary, they are reflected back into the simulation system.

In this study, all physical quantities are normalized according to a set of conventions. The time is normalized to the ion gyroperiod $\Omega_i^{-1}$ based on $B_{sh}$. The length is normalized to the ion inertial length $d_i$. The cold ion temperature is normalized to the initial temperature of cold ions. The velocity is normalized to the hot ion Alfvén velocity $v_A$ on the magnetosheath side. The electric field is normalized to $v_A B_{sh}$. The kinetic energy of the cold ions is normalized to $\frac{1}{2}m_i v_A^2$, where $m_i$ is the ion mass.

3. Simulation Results

3.1. Overview

In our simulation, we observe that the dimensionless reconnection rate peaks with $E_r \sim 0.09$ at $t \approx 18$ and becomes quasi-steady after $t \approx 30$ with $E_r \sim 0.07$ (Song et al., 2023a). However, at $t \approx 55$, the reconnection rate begins to decline due to the saturation of the tearing mode caused by the ideal conducting boundary condition. In this study, we focus on investigating the kinetics of cold ions during the quasi-steady phase.

As depicted in Figures 1a and 1b, a robust electric field $E_r$ is present at the magnetospheric separatrix region ($z \sim -1$) throughout the reconnection, pointing from the magnetosphere to the magnetosheath ($E_r > 0$). Previous simulations of asymmetric reconnection have revealed the presence of this electric field (Burch et al., 2016; Dargent et al., 2019; Malakit et al., 2013; Shay et al., 2016; Wang et al., 2017), which is balanced by the Hall term.
in generalized Ohm's law (Malakit et al., 2013; Song et al., 2023a), indicating that it is a Hall electric field. The magnitude of the Hall electric field $E_z$ at $t = 50$ (Figure 1b) is smaller than that at $t = 30$ (Figure 1a) and is weaker in the vicinity of the X-line than in the magnetospheric separatrix region (Figures 1a and 1b).

Figures 1c and 1d display the cold ion temperature, which is calculated using the following expression:

$$ T_{ic} = \frac{m}{N_{ic}} \int \left( \vec{v} - \vec{V}_{ic} \right) \cdot \left( \vec{v} - \vec{V}_{ic} \right) f_{ic} d\vec{v}, \quad (1) $$

where $N_{ic}$, $\vec{V}_{ic}$, and $f_{ic}$ represent the cold ion number density, bulk velocity, and phase space density (PSD), respectively. The white background in Figures 1c and 1d represents the absence of cold ions, which are initially located only on the magnetospheric side ($z < 0$). The cold ion temperature $T_{ic}$ exhibits little variation between $t = 30$ (Figure 1c) and $t = 50$ (Figure 1d). It reaches its maximum value near the magnetosheath separatrix. $T_{ic}$ at the magnetosheath separatrix region ($z \sim 2$) increases by approximately 30 times its initial value at both $t = 30$ and $t = 50$, while $T_{ic}$ at the X-line ($x \sim 25$) and the current sheet ($z \sim 0$) increases by approximately 20 times its initial value at both $t = 30$ (Figure 1c) and $t = 50$ (Figure 1d). However, $T_{ic}$ in the vicinity of the X-line ($x \sim 25$) decreases from $t = 30$ to $t = 50$.

To investigate the kinetics of cold ions in asymmetric reconnection, we select specific regions (marked in Figure 1c) to collect the cold ion VDFs. During the quasi-steady phase of reconnection, the cold ions exhibit similar kinetic characteristics, while the VDFs have clearer structures at $t = 30$ than at later times (not shown). Therefore, we focus on the cold ion VDFs at $t = 30$. We collect the VDFs from three main regions (Figure 1c): X-line ($24.5 < x < 25.5$), FPR ($28 < x < 29$), and outflow region ($41 < x < 42$). Each region is further divided into four subregions labeled as R1 (red rectangles, $-1 < z < 0$), R2 (white rectangles, $0 < z < 1$), R3 (black rectangles, $1 < z < 2.5$), and R4 (magenta rectangles, $2.5 < z < 4$). R1 is located in the magnetosphere, and R2 covers the magnetopause current sheet with $B_x = 0$, and R3 and R4 are situated on the magnetosheath side. Due to the larger gyro-radius of cold ions on the magnetosheath side relative to the magnetospheric side ($B_{sp}/B_{sh} = 2$), and the lower density of cold ions in the magnetosheath, we choose a larger area for R3 and R4 than for R1 and R2.

### 3.2. Cold Ion VDFs and Trajectories in the Outflow Region

Some cold ions initially in the magnetosphere can reach the magnetosheath while others cannot during the reconnection process. We classify the cold ion motions into two types according to whether they can reach the magnetosheath or not. Type 1 particles cannot reach the magnetosheath while type 2 particles are those penetrating to the magnetosheath.

The cold ions in R1, which are mainly concentrated in the range of $0 < v_{icy} < 1.2$ and $-1 < v_{icz} < 1$ (the brightest part in Figure 2c) in the outflow region (Figures 2a–2c), belong to type 1 since they do not reach the
magnetosheath, as shown later. These particles form a crescent-shaped distribution in velocity space, similar to that reported in Dargent et al. (2019). At $t = 30$, there is no significant $+x$ directional flow observed in Figure 2, indicating that the cold ion outflow has not yet reached $x = 41$. The majority of the particles drift in the $+y$ direction (Figures 2a–2f) due to the electric drift $E/B_z$. A population belonging to type 2 is observed in $-1 < v_{icy} < 0$ in R1 (Figure 2c). Three representative particles are selected from the VDF in R1 (white, blue, and red asterisks in Figures 2a–2c), and their trajectories are traced to understand the formation of the VDFs, as shown in Figure 3. Type 1 ($v_{icy} \sim 1$) and type 2 ($v_{icy} \sim 0$) particles are still present in R2 (Figures 2e and 2f) since this subregion covers the reversal line of $B_x$. Moreover, the VDFs in R2 are more discrete than those in R1.

R3 and R4 (depicted in Figures 2g–2l) are located in the magnetosheath region, and therefore, all particles in these regions belong to type 2. In both R3 and R4, counter-streaming population in the $z$-direction can be seen (Figures 2h and 2k). In the $v_{icy} - v_{icz}$ plane, the VDFs in R3 (Figure 2i) and R4 (Figure 2l) can be combined to form a ring-shaped distribution, with a gap observed around $v_{icy} \sim 1$ (Figure 2i). Additionally, some particles are not included around $v_{icy} \sim -1.5$ and $v_{icz} \sim 0$ (Figure 2l), since they are located outside of R4, specifically at $z > 4$.

The trajectories of three particles are presented in Figure 3, identified as particles 1, 2, and 3, respectively, with their respective projections in VDFs at $t = 30$ illustrated in Figures 2a–2c and marked by white, blue, and red asterisks. The left column of Figure 3 depicts the trajectory of particle 1, which performs cyclical motion and drifts in the $+y$ direction below $z = 0$, thereby located on the magnetospheric side and categorized as type 1.

Figure 2. The reduced cold ion velocity distribution functions (VDFs) in the outflow region at $t = 30$. The cold ion VDFs are collected at R1 (panels (a–c)), R2 (panels (d–f)), R3 (panels (g–i)), and R4 (panels (j–l)). The white (particle 1), blue (particle 2), and red (particle 3) asterisks in panels (a–c) denote three cold ions, whose trajectories are depicted in Figure 3.
During each period of motion, when $v_{icy}$ is at its maximum ($v_{icy} \sim 1$) and closest to the current sheet, the particle exhibits an approximately gyromotion behavior, as shown in Figure 3g. However, when $v_{icy}$ reaches its minimum ($v_{icy} \sim 0.3$), the gyromotion is influenced by the electric field force $qE_z$, where $q$ denotes the unit charge. As the particle crosses the Hall electric field layer, its motion is either accelerated ($v_{icz} > 0$) or decelerated ($v_{icz} < 0$), as shown in Figures 3d and 3g. Therefore, the motion of particle 1 is a gyromotion modulated by $E_z$. In R1, most of the particles belong to type 1 ($v_{icy} \sim 1$) and exhibit a similar behavior to particle 1 (Figure 2c).

The middle and right columns of Figure 3 depict the trajectories of particles 2 and 3, respectively. Both particles belong to type 2 as they have already entered the magnetosheath (Figures 3b and 3c) during their meandering motion in the $Y$-$Z$ plane between the magnetosphere and magnetosheath (Figures 3e and 3f). They experience acceleration by the Hall electric field $E_z$ when they move from the magnetosphere to the magnetosheath ($v_{icz} > 0$) and deceleration when they return to the magnetosphere ($v_{icz} < 0$), similar to particle 1. The hodogram of the particles’ velocity in the $v_{icy} - v_{icz}$ plane resembles a gap-ring (Figures 3h and 3i), which corresponds to the ring-shaped VDFs with a gap around $v_{icy} \sim 1$ in the $v_{icy} - v_{icz}$ plane in R3 and R4 (Figures 2i and 2l).

### 3.3. Cold Ion VDFs and Trajectories Within the FPR

The FPR is generated by the braking of the reconnection outflow between the X-line ($x = 25$ in Figure 1) and the reconnection front ($x \approx 20$ and $x \approx 30$ in Figure 1), where the reconnected magnetic field $B_z$ is piled up (e.g., Khotyaintsev et al., 2011). The cold ion VDFs within the FPR at $t = 30$ are depicted in Figure 4. The outward accelerated ion component ($v_{icz} \sim 1$) is clearly visible in Figures 4a and 4b. In the $v_{icy} - v_{icz}$ plane (Figure 4c), the background ($v_{icy} \sim 0.2$ and $v_{icz} \sim 0$), type 1 ($v_{icz} \sim -1$ or $v_{icz} \sim 1$), and type 2 particles ($v_{icy} \sim -1$) are clearly
presented. Note that the background particles have a drift velocity in the $y$-direction, $v_{icy} \sim 0.2$, which is caused by the magnetic gradient. In R2, particles with $v_{icy} \sim 1$ and $v_{icz} \sim 0$ (Figure 4d) primarily belong to type 1. The VDFs in the $v_{icy} - v_{icz}$ plane in R1 and R2 (Figures 4c and 4f) combine to form a half-ring-shaped distribution. However, this half-ring-shaped distribution differs from that in Figures 2i and 2j, which is formed by type 2 particles, whereas here it is constituted by type 1 particles. To comprehend the motion of cold ions in R2 in the $v_{icz} - v_{icy}$ and $v_{icz} - v_{icz}$ planes, we select a representative particle (marked by the blue asterisks in Figures 4d–4f) and trace its trajectory, which is discussed below.

In R3, particles exhibiting a meandering motion have a velocity component of $v_{icz} \sim \pm 1.5$, as evident from Figures 4h and 4i. A crescent-shaped distribution is visible in the $v_{icz} - v_{icy}$ plane in R3 ($v_{icz} \sim 1$) (Figure 4h). To comprehend the formation of this crescent-shaped distribution, we have selected a representative particle, marked by blue asterisks in Figures 4g–4i. In R4, a clear half-ring shape is observable in the $v_{icy} - v_{icz}$ plane (Figure 4l). This shape results from the meandering motion of cold ions belonging to type 2. These cold ions are accelerated in the $+x$ direction, which is evident from the shift of the VDFs toward the $+x$ direction in Figures 4j and 4k.

Two representative particles, labeled as particles 4 and 5, are shown in Figure 5. Their projections in the VDFs at $t = 30$ are marked by blue asterisks, as shown in Figures 4d–4f and 4g–4i. In the left column of Figure 5, the trajectory of particle 4 is displayed. Since it does not reach the magnetosheath (Figure 5a), this particle belongs to type 1. As it crosses the FPR, it performs approximately the gyromotion in the $Y-Z$ plane and $X-Y$ plane (Figure 5g), while drifting along the $-x$ direction due to the magnetic field gradient force (Figure 5c). The

Figure 4. The reduced cold ion velocity distribution functions inside the flux pileup region at $t = 30$. The format is the same as Figure 2. The blue asterisks in panels (d–f) and (g–i) denote particles 4 and 5, respectively. Their trajectories are depicted in Figure 5.
Gyromotion in the X-Y plane is due to the piled reconnected magnetic field $B_z$. The superposition of these two gyromotions results in a roughly straight-line trajectory in the $v_{icx} - v_{icz}$ plane (Figure 5e), corresponding to the oblique bunched VDF in R2 (Figure 4e).

The right column of Figure 5 depicts the trajectory of particle 5, which exhibits gyromotion due to the reconnected magnetic field $B_z$ and the Hall magnetic field $B_y$ that extends into the FPR (as shown in Figure 5f). However, the small extent of the Hall magnetic field $B_y$ within the FPR causes the particle to swiftly exit this region, resulting in a crescent-shaped distribution in the $v_{icx} - v_{icz}$ plane in R3 (as seen in Figure 4h).

Figure 5. Two representative particles’ trajectories from the cold ion velocity distribution functions inside the flux pileup region, which are marked by the blue asterisks in Figure 4. The format is similar to Figure 3. The left column shows particle 4 and the right column shows particle 5. The green, red, and blue points in panels (c–h) represent $t = 27$, $t = 30$, and $t = 40$, respectively.
3.4. Cold Ion VDFs and Trajectories Around the X-Line

Figure 6 depicts the cold ion VDFs surrounding the X-line. In R1, a crescent-shaped distribution can be observed around \( v_{iycl} \sim -1 \) (Figure 6c). These particles belong to type 2 and return from the magnetosheath. The quasi-Maxwellian distribution of particles around \( v_{iycl} \sim 0 \) and \( v_{icz} \sim 0 \) in R1 represents the background cold ions (Figures 6a–6c). The VDFs of cold ions in R2 exhibit multiple discrete structures (Figures 6d–6f). The VDFs reveal not only particles moving up and down between the magnetosphere and the magnetosheath, but also particles crossing the X-line along the \( x \)-direction. Furthermore, more particles move from the magnetosphere to the magnetosheath (\( v_{icz} > 0 \)) than in the opposite direction (\( v_{icz} < 0 \)) (Figure 6e). This observation suggests that some particles are trapped in the magnetosheath due to the change of magnetic topology caused by reconnection. The topology change deflects the particle's velocity to the \( x \)-direction.

The particles in R3 and R4, shown in Figure 6, belong to type 2 as these VDFs are collected on the magnetosheath side. These particles undergo meandering motion across the magnetopause current sheet. The VDFs in R3 (Figure 6i) and R4 (Figure 6l) can be combined to form a half-ring-shaped distribution in the \( v_{iycl} - v_{icz} \) plane, similar to the VDFs observed in the outflow region (Figures 2i and 2l) and FPR (Figure 4l). However, the VDFs around the X-line exhibit some fine structures in the \( v_{iycl} - v_{icz} \) plane in R3 and R4 (Figures 6i and 6l) that are not observed in the outflow region and FPR. The VDFs around the X-line can be divided into three parts, from which we select three representative particles (marked by the blue, white, and black asterisks in Figures 6j–6l) and trace their trajectories, labeling them as particles 6, 7, and 8, respectively.

**Figure 6.** The reduced cold ion velocity distribution functions around X-line at \( t = 30 \). The format is the same as Figures 2 and 4. The blue (particle 6), white (particle 7), and black (particle 8) asterisks in panels (j–l) denote three cold ions, whose trajectories are depicted in Figures 7 and 8.
The trajectories of three representative particles are depicted in Figures 7 and 8. The left column of both figures shows the trajectory of particle 6, which initially resides near \( z \sim -1 \) (Figures 7a and 7d). During this period, the particle's energy is relatively low (Figure 8a) and its motion is classified as type 1 (Figure 7d). At \( t \sim 21 \), the particle is accelerated by the Hall electric field \( E_z \), which quickly converts its motion to type 2, performing meandering motion (Figures 7d, 8a, and 8j). Particle 6 departs from the X-line region shortly after entering region R4, which is evident from the alternating sign change of the magnetic field \( B_x \) (Figure 8d) and the particle velocity \( v_{icz} \) (Figure 8g). While the reconnection electric field \( E_y \) decelerates type 1 particles \((t < 28)\), it accelerates particle 6 after switching to type 2 (Figure 8j). Given that the number of type 1 particles is significantly larger than that of type 2, \( E_y \) does negative work on the cold ions overall (Song et al., 2023a). Notably, the reconnection electric field \( E_y \) is negative around the X-line (i.e., \( E_y < 0 \)), whereas the type 1 particles have a positive velocity \( v_{icy} > 0 \) due to their gyromotion (Figure 7g). Thus, the large number of type 1 particles are decelerated by \( E_y \) (i.e., \( qv_{icy}E_y < 0 \)).

Particle 6 suggests that the innermost particles in the \( v_{icy} - v_{icz} \) plane (Figure 6l) originate from the left and right sides of the X-line and possess large thermal velocities in the x-direction.

The trajectories of particles 7 and 8 are illustrated in the middle and right columns of Figures 7 and 8, respectively. Both particles belong to type 2 and perform meandering motion (Figures 7e and 7f). Particle 7 starts performing meandering motion at \( t = 25 \) (Figure 7e), while particle 8 starts at \( t = 0 \) (Figure 7f). Meandering motion is evidenced by the alternating sign changes of the magnetic field \( B_z \) along the particle trajectory (Figures 8e and 8f) as well as the particle velocity \( v_{icz} \) (Figures 8h and 8i), forming a ring-shaped distribution in the \( v_{icy} - v_{icz} \) plane (Figures 6i and 6l). They gain or lose energy as they pass through the Hall electric field layer, for example, gaining energy at \( t = 26 \) and losing energy at \( t = 34 \) for particle 7 (Figure 8k), while gaining energy at \( t = 5 \) and losing energy at \( t = 12 \) for particle 8 (Figure 8l). These two particles have different numbers of meandering cycles when they are recorded in R4 (marked by the red dots), that is, \( \sim 0.5 \) cycles for particle 7 (Figure 7e) and \( \sim 2.5 \) cycles for particle 8 (Figure 7f). During each meandering cycle, their energy increases slightly. \( E_z \) accelerates the particles.
step by step, for example, the energy of particle 8 at $t = 25$ is greater than that at $t = 15$ (Figure 8l). During meandering motion, both particles are accelerated by $E_y$ (Figures 8k and 8l). Therefore, the separation of the highest and middle energy parts of the VDF in R4 is caused by the different number of meandering cycles (Figure 6l).

We present the profiles of $E_z$ along $x = 25$ at different times to show that the particle can gain energy from $E_z$ for each meandering cycle (Figure 9a), along with the integration of $qE_z$ from $z = -1$ to $z = 4$ as a function of time (Figure 9b). The magnitude of the peak $E_z$ reaches $\sim 1.9$ at $t = 30$ and reduces to $\sim 1.4$ at $t = 50$ (Figure 9a), indicating that the amplitude of $E_z$ reduces over time. We also observe that the work done by $E_z$ decreases as the cold ions cross the Hall electric field layer (Figure 9b). Here, we denote the positive work done by $E_z$ when a cold ion moves from the magnetosphere to the magnetosheath as $W_1$, and the negative work done by $E_z$ when it returns from the magnetosheath to the magnetosphere as $-W_2$. As the electric field $E_z$ weakens, then $W_1 - W_2 > 0$. It is important to note that the cold ions are initially in the magnetosphere and can gain energy from $E_z$ during each meandering motion, which is a step-by-step acceleration process. This acceleration mechanism occurs not only around the X-line but also in the outflow region. For instance, for particle 3, the energy at $t = 29$ (Figure 3f, $y \approx -24$, and $z \approx -1.6$) is lower than the energy at $t = 39$ (Figure 3f, $y \approx -33$ and $z \approx -1.6$). Similarly, the energy at $t = 39$ is lower than the energy at $t = 50$ (Figure 3f, $y \approx -38$ and $z \approx -1.6$).

### 3.5. Cold Ion Heating

To investigate the cold ion heating process, we conduct a comparison of the cold ion PSDs at different times. Figure 10 illustrates the cold ion PSDs $f_{i_6}(z, v_{ex})$ and $f_{i_7}(z, v_{ex})$ in the X-line, FPR, and outflow region at $t = 30$ and $t = 50$. At the X-line, below $z = 0$, a large number of background cold ions are present. The PSD is symmetric about $v_{ex} = 0$ (Figures 10a and 10d). The particles near $v_{ex} \approx 0$ in regions of $z > 0$ undergo meandering motion (Figures 10a and 10d). Furthermore, we see particles from both the left and right sides of the X-line (Figures 10a
and 10d), which is consistent with the reduced VDF around the X-line displayed in Figures 6d and 6e. The PSD $f_{ic}(z, v_{icz})$ exhibits a ring-shaped distribution as a result of the particles’ meandering motion (Figures 10g and 10j). At the X-line, the particle movement is nearly linear ($0 < z < 2$) due to the weak magnetic field, manifested as the straight boundary in $0 < z < 2$ and $v_{icz} = \pm 1$ (Figures 10g and 10j). The PSD at $t = 50$ is more spread out in velocity space as compared to $t = 30$ around the X-line, indicating that the cold ions are heated there.

At $t = 30$, the cold ion outflow in the $x$-direction ($v_{icx} \sim 1$) is clearly visible in the FPR (Figure 10b). The PSD $f_{ic}(z, v_{icz})$ consists of both type 1 and 2 particles, as shown in Figure 10h. The type 2 particles perform meandering

Figure 9. (a) Profiles of the electric field $E_z$ along $x = 25$ at $t = 30$ (red), $t = 40$ (black), and $t = 50$ (blue). (b) The cumulative work done by the electric field $E_z$ along $x = 25$ from $z = -1$ to $z = 4$ as a function of time.

Figure 10. The phase space density of cold ions $f_{ic}(z, v_{icz})$ (panels (a–f)) and $f_{ic}(z, v_{icz})$ (panels (g–l)) at the X-line (left column), flux pileup region (FPR) (middle column), and outflow region (right column). Panels (a–c) and (g–i) show the results at $t = 30$, while panels (d–f) and (j–l) show the results at $t = 50$. 
motion, resulting in a large ring \((-1 < z < 4)\), while the type 1 particles exhibit approximate gyromotion, forming a small ring \((-1 < z < 1)\) (Figure 10h). The diffused PSD at \(t = 50\) (Figures 10e and 10k) indicates that the cold ions undergo heating, resulting in the filling of the void between the counter-streaming components and the formation of a single core VDF, corresponding to the bulk heating.

At \(t = 30\) in the outflow region, the cold ions are predominantly near \(v_{\text{icx}} \sim 0\) (Figure 10c). Unlike the PSD at the X-line (Figure 10a), there is no noticeable population moving in the \(x\)-direction. The small circle \((-1 < z < 0)\) and large circle \((0 < z < 4)\) observed at \(t = 30\) (Figure 10i) are formed by particles of types 1 and 2, respectively, similar to the PSD within the FPR (Figure 10h). The intersection at \(z \sim 0.4\) and \(v_{\text{icx}} \sim 0\) (Figure 10i) is caused by particles exhibiting a motion similar to that of particle 3, resulting in intersection points when they perform meandering motion. At \(t = 50\), a bulk flow is observed in the +\(x\) direction on the magnetospheric side \((-1 < z < 0\) and \(v_{\text{icx}} > 1)\) and in the −\(x\) direction on the magnetosheath side \((3 < z < 4\) and \(v_{\text{icx}} < 0)\) (Figure 10f). At this time, the ring formed by the type 1 particles is no longer visible \((-2 < z < 0)\) (Figure 10i), but the ring formed by the type 2 particles is still evident \((0 < z < 4)\). This suggests that on the magnetospheric side, the cold ions are heated, while the temperature increase on the magnetosheath side is not attributed to bulk heating, but rather to a pseudothermal effect.

4. Discussion and Summary

This paper presents a comprehensive analysis of the kinetic behavior of cold ions in various regions of asymmetric reconnection, encompassing VDFs and trajectories of cold ions, with the objective of enhancing our understanding of the energization and heating process of cold ions in asymmetric reconnection. The VDFs of cold ions consist of two distinct types: type 1 cold ions that are unable to reach the magnetosheath and type 2 cold ions that are able to reach the magnetosheath. Our main results are summarized as follows:

1. The motion of type 1 particles is primarily dominated by gyromotion, which is modulated by the Hall electric field \(E_y\) on the magnetospheric side. In contrast, the motion of type 2 particles is characterized by meandering motion.

2. The reconnection electric field \(E_z\) does negative work on type 1 particles and positive work on type 2 particles. Additionally, type 2 particles are accelerated in a step-by-step manner due to the gradually decreasing Hall electric field \(E_y\) over time.

3. The meandering motion of type 2 particles generates a ring-shaped distribution in the magnetosheath, while the gyromotion of type 1 particles produces a ring-shaped distribution in the magnetospheric separatrix region.

4. In the later stage of the reconnection \((t = 50)\), the increase in the temperature of cold ions is bulk heating at the magnetospheric separatrix region, FPR, and the X-line, while it is a kinetic effect in the magnetosheath.

As a result of the reduction in the Hall electric field, type 2 particles can be gradually accelerated in a step-by-step manner, while type 1 particles cannot. Type 2 particles exhibit meandering motion, with one motion cycle lasting approximately \(10 \Omega_{\text{ic}}^{-1}\) (particles 2, 3, 7, and 8). In contrast, type 1 particles exhibit gyromotion, with one cycle lasting approximately \(3 \Omega_{\text{ic}}^{-1}\) (particles 1 and 6). The longer motion period of type 2 particles means that when they pass through the Hall field twice within a cycle, the Hall field undergoes substantial changes. In contrast, the shorter motion period of type 1 particles results in acceleration when they pass through the Hall field and deceleration shortly thereafter. Therefore, the Hall field changes experienced by type 1 particles are relatively smaller, making them gain less energy in a stepwise manner.

In our simulation, the step-by-step acceleration of type 2 particles is attributed to the diminishing Hall electric field \(E_y\) in the magnetospheric separatrix region. It is important to acknowledge that whether the Hall electric field decreases over time is contingent upon the initial parameters of the simulation, including factors such as the ratio of magnetic field strength \(B_{\text{sh}}/B_{\text{ms}}\), \(\beta\), among others. Further investigation should be necessary to explore the connection between the Hall electric field and the asymmetric simulation parameters.

Type 2 particles perform meandering motion across the current sheet, resulting in similar features in the VDFs recorded in R3 and R4 in the X-line, FPR, and outflow regions. These VDFs show a ring-shaped distribution. Furthermore, VDF in R1 shows the particles returning from the magnetosheath to the magnetosphere in all these three regions. While background particles are observed at the X-line, they are no longer present in the outflow region due to their acceleration by \(E_y\). The VDFs at the FPR are intermediate between those of the X-line and
outflow regions. At the FPR, background cold ions constituting a quasi-Maxwellian distribution with a drift velocity ($v_{ciy} \sim 0.2$) are observed in R1.

During the quasi-steady reconnection phase ($t = 30–50$), the cold ion temperature increases by 20–30 times compared to its initial value. Between $t = 30$ and $t = 50$, there is a transition from kinetic effects to bulk heating. Despite the bulk heating of the cold ions, their temperature does not change significantly during this period, which may seem counterintuitive. This can be explained by the difference between kinetic and thermodynamic temperatures. Considering a multi-beam plasma with zero thermal energy for each beam, its temperature $T$ is not zero, which can be calculated by Equation 1. Similarly, a plasma with a Maxwellian VDF can also be constructed with a temperature $T$. Even though both exhibit the same temperature, the former's temperature is kinetic, while the latter's temperature is a true temperature in the thermodynamic sense (Baumjohann & Treumann, 1996). In our simulation, we can see counter-streaming or ring-shaped population at $t = 30$. Although the temperature calculated by Equation 1 is very high, the cold ions are not fully heated. By $t = 50$, the number of low-energy particles increases, filling the gap between the counter-streaming or ring-shaped VDFs (Figure 10), and the number of high-energy particles decreases slightly (e.g., the particles at $v_{ciy} \sim -1$ in Figure 10j and $v_{ciy} \sim 1$ in Figure 10l decrease), indicating bulk heating of the cold ions. It should be noted that even at $t = 50$, the cold ion VDFs around the current sheet still deviate significantly from the Maxwellian VDF. It takes a long time for the cold ions within the current sheet to form a Maxwellian VDF.

As a result, to determine whether the temperature increase of cold ions is caused by bulk heating or only “pseudothermal” (Goldman et al., 2020, 2021), it is necessary to examine the particle VDFs. In addition, a significant positive gradient is formed in $f(v)$ as clearly shown in Figure 10. This type of VDF is unstable to trigger various plasma waves (e.g., Deng et al., 2010, 2009; Khotyaintsev et al., 2019; Shuster et al., 2021; Toledo-Redondo et al., 2021; Zhou et al., 2016, 2009a, 2009b), which may feedback to the reconnection process and affect the cold ion dynamics. Further studies are worth performing to investigate the wave-particle interactions caused by cold ions.

Data Availability Statement

The data that support the findings of this study are available at https://doi.org/10.5281/zenodo.7794163 (Song et al., 2023b).

References


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