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Key Points:

- Magnetic reconnection in a magnetopause-like geometry is experimentally studied in Space Plasma Environment Research Facility
- Bipolar and Quadrupole Hall magnetic fields confirm that reconnection is in Hall regime
- Reconnection evolves from asymmetric multiple x -line state to symmetric single x -line state

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Laboratory Realization of Magnetopause-Like Reconnection in Space Plasma Environment Research Facility (SPERF)

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Abstract Magnetic reconnection explosively converts magnetic energy into plasma heating and particle acceleration. At Earth's magnetopause, reconnection governs solar wind-magnetosphere coupling and drives global convection. Understanding these processes requires resolving reconnection's spatiotemporal evolution, which is difficult for in situ observations but achievable in laboratory experiments. However, building a geometry like the real magnetopause in laboratory remains a key challenge. Here, we present the first laboratory experiment at the Space Plasma Environment Research Facility trying to replicates Earth's magnetopause configuration. Using a dipole magnet (mimicking magnetosphere) and coaxial flux cores (simulating solar wind), we establish a magnetopause-like current sheet via dynamic plasma compression. Measured Hall magnetic fields confirm Hall reconnection, transitioning from an asymmetric multiple x -lines state to a symmetric single x -line state. This dynamic evolution will impact global energy conversion and transport at magnetopause.

Plain Language Summary The interaction between solar wind and Earth's magnetosphere forms a boundary layer named magnetopause, where a fundamental plasma process, magnetic reconnection, usually takes place. During magnetopause reconnection, a huge amount of energy can be released, leading to explosive geomagnetic activities. Although magnetopause reconnection has been extensively studied by satellite observations, its spatial and temporal evolution have not been well understood because of the limited spacecraft trajectories. Here, taking advantage of the repeatability and controllability of laboratory plasma experiment, we try to experimentally study magnetopause reconnection by building a magnetopause-like geometry in a new device: Space Plasma Environment Research Facility. The results show dynamic evolution of reconnection with features similar to previous observations and simulations. We believe this platform will greatly advance studies of the interaction between solar wind and planetary magnetosphere.

1. Introduction

Magnetic reconnection, a universal plasma process that explosively converts magnetic energy into plasma heating and particle acceleration, powers some of the most energetic phenomena in the universe, from solar flares and magnetospheric substorms to gamma ray bursts (Angelopoulos et al., 2008, 2020; Kumar & Zhang, 2015; Lu et al., 2022; Lyutikov & Lazarian, 2013; Masuda et al., 1994; Shibata et al., 1995). For planets with intrinsic magnetic field like Earth, the interaction between their magnetosphere with solar wind forms a boundary layer named magnetopause (DiBraccio et al., 2013; Frey et al., 2003; Huddleston et al., 1997; McAndrews et al., 2008; Paschmann et al., 1979; Phan et al., 2000; Slavin et al., 2009; Sonnerup et al., 1981; Walker & Russell, 2012). Magnetic reconnection is one of the most important processes take place at magnetopause because it mediates the transfer of solar wind energy into the magnetosphere, driving global convection and substorms (Burch et al., 2016; Dai et al., 2024; Dungey, 1961). Magnetopause reconnection usually occurs under strong solar wind compression and significant plasma asymmetries, leading to dynamic evolution of reconnection region with complex structures. Satellite missions (e.g., Cluster, THEMIS, MMS) have identified some key reconnection

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features such as the Hall magnetic and electric fields (Mozer et al., 2002; Tanaka et al., 2008; Vaivads et al., 2004; R. Wang, Nakamura, et al., 2017), the formation and interaction of magnetic flux ropes (Øieroset et al., 2011; Sonnerup et al., 2004; R. Wang, Lu, et al., 2017; Zhou et al., 2017). However, these observations are inherently limited to measurements along spacecraft trajectories, the time-dependent and global evolution of magnetopause reconnection, which are important for the energy conversion and transport processes, remains incompletely understood.

Laboratory experiments have emerged as critical tools to resolve these spatiotemporal gaps (Ji et al., 2023). Facilities such as VTF (Egedal et al., 2003), MRX (Ji et al., 1998; Yamada et al., 2014, 2018), TREX (Greess et al., 2021; Olson et al., 2016), PHASMA (Shi et al., 2022, 2023), and KLMP (Sang et al., 2022; F. Yang et al., 2025) have made great progresses in understanding fundamental problems in reconnection through delicate experiment design and precise diagnostics, yet replicating the magnetopause's geometry and driven conditions has remained a frontier challenge. To address this, the Space Plasma Environment Research Facility (SPERF) was developed, which is a large-scale cylindrical device with a length of 10.5 m and a diameter of 5 m. SPERF uniquely integrates a dipole magnet (emulating Earth's dipole field) with four pulsed coaxial flux cores (simulating solar wind magnetic fields). This configuration compresses a high-speed plasma against the dipole field, self-consistently forming a magnetopause-like current sheet with parameters directly scalable to space conditions (Ling et al., 2022, 2024).

In this work, we employ SPERF to experimentally study magnetopause reconnection. High-resolution measurements detect Hall magnetic field consistent with spacecraft observations, indicating the process of Hall reconnection. The reconnection current sheet has a two-stage evolution: an initial asymmetric phase, marked by multiple reconnection x -lines and magnetic island formation, transitions to a symmetric single x -line regime. Although the spatial scale and Lundquist number of the current experiment remain far different from Earth's magnetopause, our results provide valuable interpretation for the dynamic evolution of magnetopause-like reconnection, demonstrating the capability of SPERF to establish a scalable platform for studying space plasma physics in laboratory.

2. Experimental Setup

Figure 1a shows a schematic of SPERF. The experiment setup is as follows. An electron cyclotron resonant (ECR) plasma source is triggered first to inject microwave into the apparatus constantly. Then, data acquisition for the magnetic field begins at time 0, and a slow pulsed current is driven in the dipole magnet at 2 ms to create a dipole magnetic field. A quasi-steady model magnetosphere is built when the current peaks at 19 ms, at the same time, the poloidal field (PF) coils of the four flux cores are driven by rapid pulsed currents to create the model solar wind magnetic field. After a delay of 50 μ s, the model solar wind plasma is inductively generated around the flux cores by their toroidal field coils driven by rapid pulsed currents. The simulated solar wind expands outwards and compresses the model magnetosphere, inducing magnetic reconnection, as shown in Figure 1b. The time sequence of the experiment is detailed in Figure 1c. In the following of this paper, we will omit “model” before “magnetosphere” and “solar wind” for simplification. Argon is used as the discharging gas, and the fill pressure is set as 0.5 Pa. Some typical plasma parameters are summarized in Table 1.

We use a coordinate system similar to the GSM coordinate system: The origin point is located at the center of the dipole magnet, x -axis points to the four flux cores horizontally, z -axis points upward vertically, and y -axis completes the right-hand system (see Figure 1b). A movable 3D magnetic probe array is adopted to measure the three components of the magnetic field at 16×21 locations spanning a region of 32×84 cm centered at $x = 150$ cm and $z = 0$ in the $y = 0$ plane (J. Yang et al., 2024). The magnetic probe array is made of miniature commercial inductive coils, whose areas have good uniformity. They are calibrated by a Helmholtz coil. The magnetic field measurement errors are smaller than 10%. The response frequency of the magnetic probes is better than 300 kHz, and their spatial resolution is about 5 mm. The Langmuir probes with four tips are used for plasma density and electron temperature measurements. Their temporal and spatial resolutions are better than 0.5 μ s and 10 mm. The errors of the electrostatic measurement are lower than 50%.

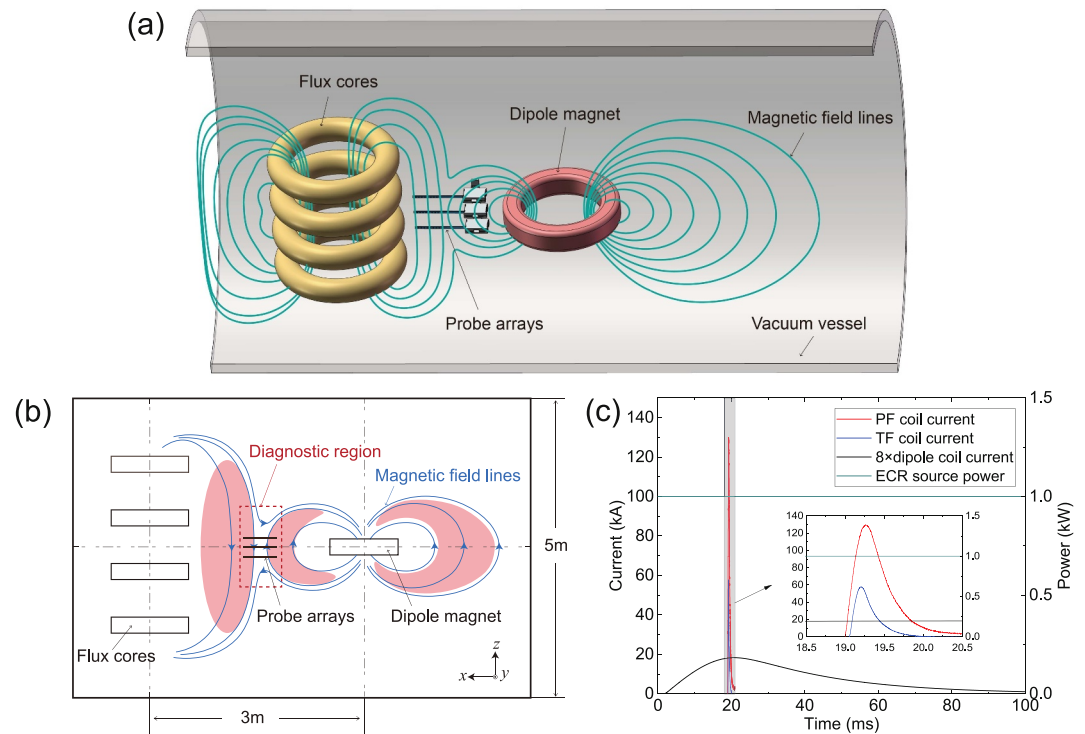


Figure 1. (a) A schematic of Space Plasma Environment Research Facility (SPERF). (b) A sketch of the magnetopause reconnection experiment in SPERF and our diagnostic region. (c) The time sequence of the experiment.

3. Experimental Results

3.1. Spatial Distribution of Magnetic Field

Figure 2 shows the spatial distribution of the three components of magnetic field at $t = 19.135$ ms, during the growth phase of the driving current in the flux cores. In Figure 2a, B_x shows clear bipolar structure corresponding to a magnetic island, which is bounded by two reconnection x -lines. On the solar wind side, the amplitude of B_z can reach 200 Gs, while on the magnetosphere side, it is only around 100 Gs. The electron density on the solar wind side (around 10^{13} cm^{-3}) is also an order of magnitude higher than that on the magnetosphere side (around 10^{12} cm^{-3}). Therefore, reconnection is asymmetric during this period. However, the magnetic field asymmetry is a little different from Earth's magnetopause, where it is stronger on the magnetosphere side. The reason might be that the driving current in the flux cores is too large compared with that in the dipole magnet. In Figure 2b, we notice that B_y shows a bipolar distribution around both x -lines, where it is negative above the x -line and is positive below the x -line. In Figures 2d and 2e, we plot the line profiles of B_z and B_y along the two horizontal dashed lines in Figures 2b and 2c, crossing the bipolar B_y patterns below the top x -line and above the bottom x -line, respectively. The positive B_y located around $B_z = 0$ in Figure 2d is clear. In Figure 2e, there is a negative background B_y , we can still identify a negative peak of B_y around $B_z = 0$. The polarization of the bipolar B_y structure also agrees with the Hall magnetic field during asymmetric reconnection, where it is formed due to the Hall current carried mainly by electrons penetrate the magnetosphere from the solar wind (Pritchett, 2008; Shay et al., 2016).

In this period, the typical magnetic field is $B = 200$ Gs, electron density is $n_e = 2 \times 10^{13} \text{ cm}^{-3}$, electron temperature is $T_e = 20$ eV. Then, the Lundquist number is around $S = 1,300$, and the system size normalized by ion inertia length is around $\lambda = L/d_i = 3.1$. The system is in single x -line collisionless regime based on the phase diagram of reconnection (Ji & Daughton, 2011). However, multiple x -line reconnection with magnetic island still develops, similar result was also obtained in previous works (Stenzel &

Table 1

Typical Parameters for the Magnetopause Reconnection Experiment in Space Plasma Environment Research Facility

Parameters	Solar wind value	Magnetosphere value
Reconnecting magnetic field B	100–200 Gs	50–100 Gs
Plasma size L	1 m	1 m
Electron density n_e	$(1-2) \times 10^{13} \text{ cm}^{-3}$	$(0.5-2) \times 10^{12} \text{ cm}^{-3}$
Electron temperature T_e	5–20 eV	5–10 eV
Lundquist number S	80–1,800	130–1,500
Mean free path l	1.8–57.6 cm	18–288 cm

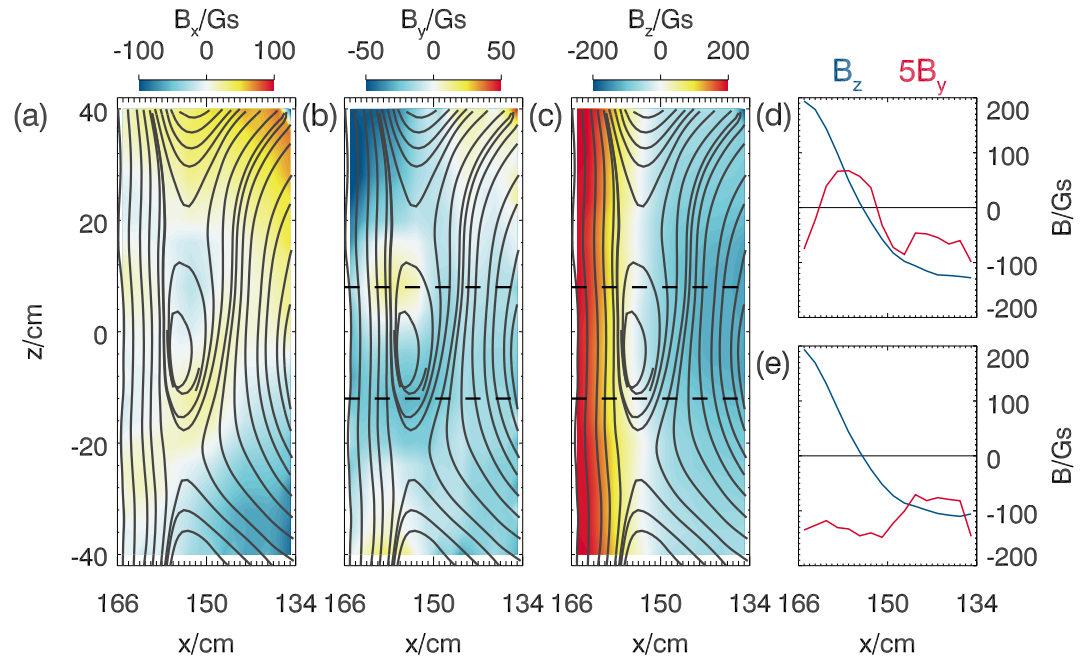


Figure 2. (a–c) The spatial distribution of the three components of magnetic field at $t = 19.135$ ms, the black curves represent the in-plane magnetic field lines. (d, e) The line profiles of B_z and B_y along the two horizontal dashed lines in panels (b, c).

Gekelman, 1981; Xie et al., 2024; Yamada et al., 1997). For our experiment, the formation of the two x -lines is related to the non-uniform drive from the four flux cores.

Figure 3 shows the spatial distribution of the three components of magnetic field at $t = 19.37$ ms, during the early decay phase of the driving current. The distributions of B_x and B_z show a typical single x -line geometry. B_y shows a quadrupole distribution, and the polarization is consistent with the Hall magnetic field. In Figures 3d and 3e, the

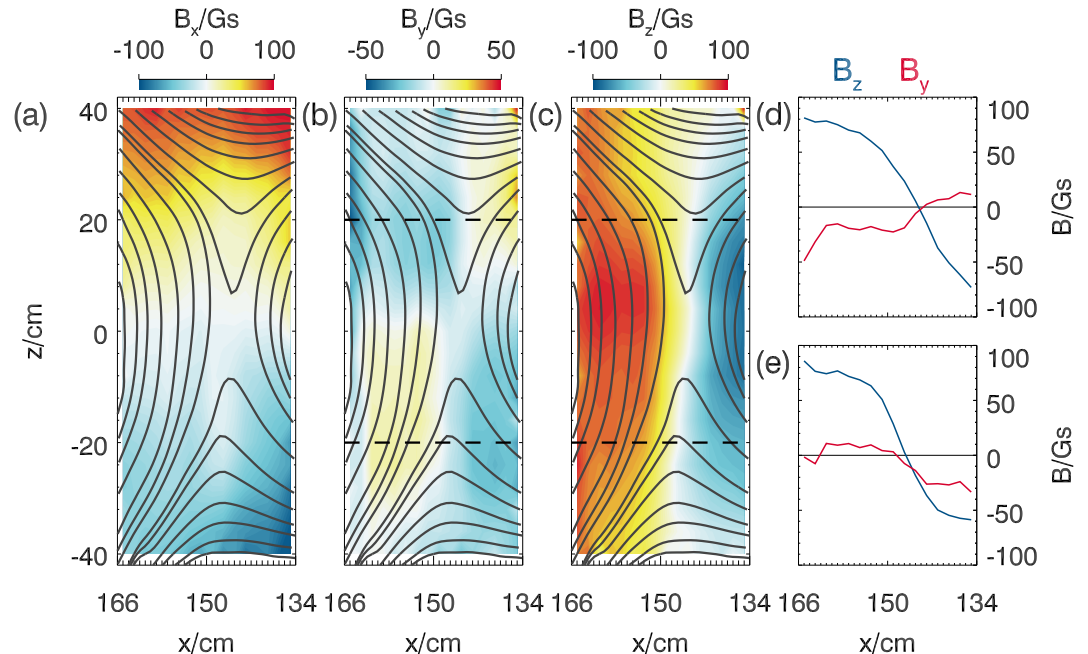


Figure 3. (a–c) The spatial distribution of the three components of magnetic field at $t = 19.37$ ms, the black curves represent the in-plane magnetic field lines. (d, e) The line profiles of B_z and B_y along the two horizontal dashed lines in panels (b, c).

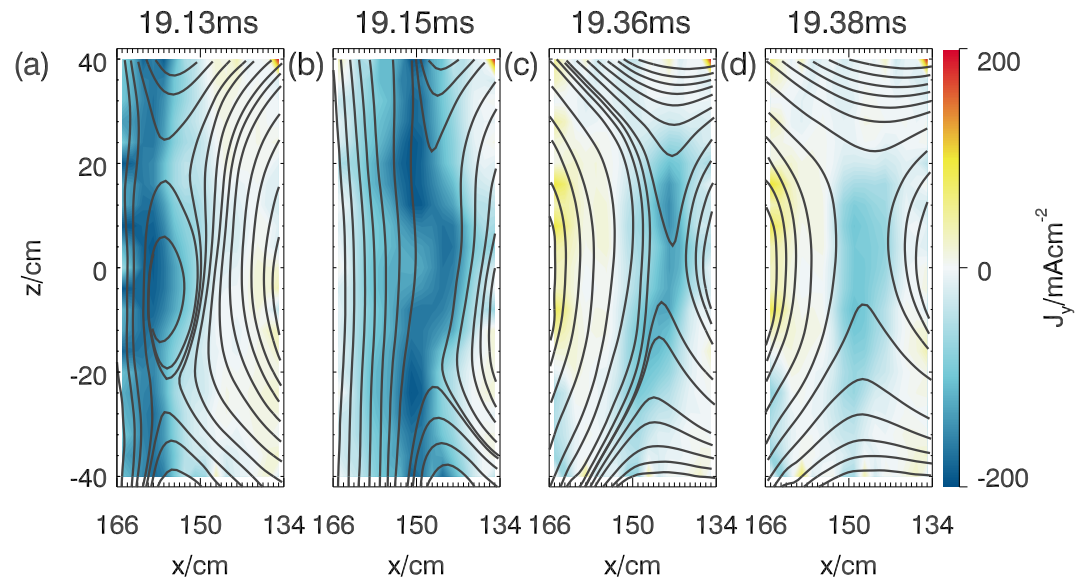


Figure 4. The time evolution of the reconnection current sheet at $t = 19.13, 19.15, 19.36$, and 19.38 ms. The current density is calculated by $J_y = (\partial_z B_x - \partial_x B_z)/\mu_0$ using the measured magnetic field B_x and B_z . The black curves represent the in-plane magnetic field lines.

amplitude of the Hall magnetic field B_y can reach 10%–30% of the upstream magnetic field B_z , it is also consistent with previous studies (Eastwood et al., 2010). In this period, the typical magnetic field is $B = 100$ Gs, electron density is $n_e = 10^{12} \text{ cm}^{-3}$, electron temperature is $T_e = 10$ eV. Then, the Lundquist number is around $S = 1,000$, and the system size normalized by ion inertia length is around $\lambda = L/d_i = 0.7$. The system is also in single x -line collisionless regime.

Besides these two time slices, Hall magnetic field persists for a long time during the experiment, indicating that reconnection in our experiment is in the Hall regime. Distinct distributions of Hall magnetic field at different stages also indicate dynamic evolution of the reconnection current sheet, which will be presented in Section 3.2.

3.2. Time Evolution of the Reconnection Current Sheet

During the growth phase of the driving current in the PF coils, the solar wind expands and greatly compresses the magnetosphere. As a result, the reconnecting current sheet sweeps through our probe arrays from the left side to the right side, and then, the reconnecting current sheet moves back due to the rebound of magnetosphere. The time evolution of the reconnection current sheet is shown in Figure 4. In Figures 4a and 4b, the current sheet moves from left to right, while in Figures 4c and 4d, the current sheet is rebounded from right to left. Here, the current density $J_y = (\partial_z B_x - \partial_x B_z)/\mu_0$ is calculated using the measured magnetic field B_x and B_z . In Figures 4a and 4b, the current density J_y is stronger, and the current sheet is long in the z direction. The magnetic field lines show multiple x -line geometry with a magnetic island in Figure 4a. This magnetic island has formed before $t \approx 19.12$ ms, when the current sheet starts to move into our diagnostic region, and it disappears at $t \approx 19.14$ ms. In Figures 4c and 4d, the current density is a little weaker, and the current sheet is short, strong current density only displays near the x -line.

The motion of the reconnection current sheet can be identified clear in Figure 5a, which shows the time stack of the distribution of J_y along the x direction. The current sheet can be observed during two time periods, $t = 19.12$ – 19.17 ms and $t = 19.31$ – 19.38 ms, corresponding to the growth phase and early decay phase of the driving current shown in Figure 5b.

Figures 5c and 5d plot the time evolution of the location and the half width of the current sheet. At each time slice, we fit the J_y distribution along x using a function with the form of $f(x) \sim \cosh^{-2}((x - x_0)/\delta)$, the fitted x_0 and δ are chosen to be the location and half width of the current sheet. From Figure 5c, we can estimate the motion speeds of the current sheet during the two periods, which are around -5.6 and 1.7 km/s. This motion agrees well with the prediction from the particle-in-cell simulation of magnetic reconnection experiment in SPERF (Huang

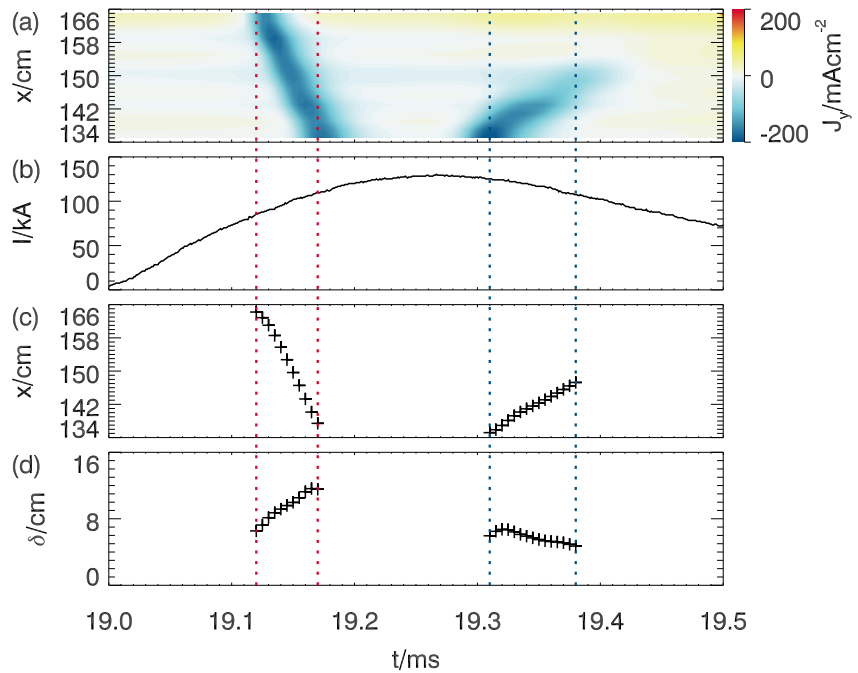


Figure 5. (a) The time stack of the distribution of J_y along the x direction. (b) The amplitude of the driving current in the poloidal field coils in the flux cores. (c) The time evolution of the location of the reconnection current sheet in the x direction. (d) The half width of the reconnection current sheet. The red and blue dashed lines bound the two time periods during which we measure the current sheet.

et al., 2025). During the first period, the model solar wind magnetic field B_z is around 200 Gs, and the electron density is around $n_e \approx 1 \times 10^{13} \text{ cm}^{-3}$, then the Alfvén speed is around $V_A \approx 21.8 \text{ km/s}$. So, the normalized motion velocity of the reconnection current sheet is around $0.26 V_A$, which can be regarded as the expanding speed of the solar wind. This driving speed is sub-Alfvénic, but a little larger than the typical reconnection inflow speed $0.1 V_A$. As a result, magnetic flux is piled up in the reconnection inflow region and the magnetosphere is greatly compressed. The motion of Earth's magnetopause current sheet in the normal direction is also frequently observed by satellite, and the average speed is around 40 km/s (Paschmann et al., 2018; Phan & Paschmann, 1996). Based on the typical Alfvén speed $V_A = 200\text{--}500 \text{ km/s}$ in the magnetosheath, the average motion speed of Earth's magnetopause current sheet is $0.08\text{--}0.2 V_A$, comparable to that in our experiment.

In Figure 5d, the average half width of the reconnection current sheet is around 9.5 cm during the first period. Based on the measured local electron density $n_e \approx 2 \times 10^{13} \text{ cm}^{-3}$ using the Langmuir probes, the local ion and electron inertia lengths are $d_i = 32.2 \text{ cm}$ and $d_e = 0.12 \text{ cm}$. Therefore, the half width of the reconnection current sheet is on the sub-ion scale, $\delta \approx 0.3 d_i \approx 80 d_e$. The sub-ion scale current sheet may be related to the broaden of the current sheet due to the magnetic island or some collision effects due to the short mean free path during this period. During the second period, the average half width is around 5.7 cm. Based on the local electron density $n_e \approx 1 \times 10^{12} \text{ cm}^{-3}$, the local ion and electron inertia lengths are $d_i = 144.2 \text{ cm}$ and $d_e = 0.53 \text{ cm}$. Therefore, the half width of the reconnection current sheet is on the electron inertia scale, $\delta \approx 11 d_e$, comparable to MRX experiments which obtain $\delta \approx 5.5\text{--}7.5 d_e$ (Ren et al., 2008), indicating the formation of a current sheet mainly carried by electrons.

4. Conclusions and Discussion

In this paper, we experimentally study magnetopause-like reconnection using SPERF. A magnetic geometry similar to Earth's magnetopause reconnection is firstly built in laboratory. During the experiment, we show the compression and rebound of the magnetosphere driven by the solar wind, and a reconnection current sheet is formed therein. During the first period, reconnection is asymmetric, and a bipolar Hall magnetic field is measured, the reconnection current sheet is long and multiple x -line reconnection develops with the formation of a magnetic

island. During the second period, we observe a symmetric single x -line reconnection with quadrupole Hall magnetic field.

Laboratory study of asymmetric reconnection has been conducted in MRX, TREX, and OMEGA laser facility (Olson et al., 2016; Rosenberg et al., 2015; Yamada et al., 2018; Yoo et al., 2014, 2017), these experiments also apply to understand magnetopause reconnection. Compared with these works, the magnetic geometry and driving conditions are more similar to Earth's magnetopause in our experiment. We observe the compression and rebound of the magnetosphere, and the evolution of magnetic reconnection from an asymmetric, multiple x -line state to a symmetric, single x -line state for the first time. These results indicate that magnetopause reconnection is highly unsteady, where the degree of upstream asymmetry and the number of x -line can change rapidly. The degree of asymmetry between magnetosphere and magnetosheath can mediate the reconnection rate (Cassak & Shay, 2007; Liu et al., 2018) and energy conversion rate (Chang et al., 2023), which affect the global convection process. The change in the number of reconnection x -line is closely related to the formation and interaction of flux ropes, which greatly affect particle acceleration and energy transport processes at magnetopause. The formation of flux ropes through multiple x -line reconnection can also explain the flux transfer events typically observed at the magnetopause of Earth and other planets (Lee & Fu, 1985; Russell & Elphic, 1978; Slavin et al., 2010; Walker & Russell, 2012). This mechanism has been demonstrated by satellite observations and simulations (Chen et al., 2017; Guo et al., 2021; Hasegawa et al., 2010; Sun et al., 2019; Zhong et al., 2013). Our results further provide experimental evidence for this explanation.

In the current experiment, we use Argon plasma, the driving voltage in the coils and the ECR source power are also low. As a result, the spatial scale of the reconnection region normalized by ion inertia length is around $1\text{--}3 d_i$, and the Lundquist number is around 10^3 . Both are too small compared with Earth's magnetopause. In the future, we will use Helium or Hydrogen plasma, and increase the driving voltage and the ECR power. Then we expect to have a reconnection region around $10\text{--}20 d_i$, it is still too small compared with Earth, but comparable to Earth like planets such as Mercury. This will enable more comprehensive studies on three-dimensional, driven, magnetopause reconnection.

SPERF is a new platform opened to the world which is devoted to study fundamental physical processes in the magnetosphere. The results from SPERF can also support the upcoming joint CAS/ESA mission Solar Wind Magnetosphere Ionosphere Link Explorer (SMILE), which will study the interaction between the solar wind and Earth's magnetosphere via X-Ray and UV images of the magnetosphere and aurora (C. Wang & Branduardi-Raymond, 2018).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The experiment data and scripts used to plot the figures are available at National Space Science Data Center, National Science and Technology Infrastructure of China via Huang (2025).

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Acknowledgments

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