A LABORATORY EXPERIMENT OF MAGNETIC RECONNECTION: OUTFLOWS, HEATING, AND WAVES IN CHROMOSPHERIC JETS

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ABSTRACT

Hinode observations have revealed intermittent recurrent plasma ejections/jets in the chromosphere. These are interpreted as a result of non-perfectly anti-parallel magnetic reconnection, i.e., component reconnection, between a twisted magnetic flux tube and the pre-existing coronal/chromospheric magnetic field, though the fundamental physics of component reconnection is not revealed. In this paper, we experimentally reproduced the magnetic configuration and investigated the dynamics of plasma ejections, heating, and wave generation triggered by component reconnection in the chromosphere. We set plasma parameters as in the chromosphere (density 10^{14} cm^{-3}, temperature 5–10 eV, i.e., (5–10) × 10^{4} K, and reconnection magnetic field 200 G) using argon plasma. Our experiment shows bi-directional outflows with the speed of 5 km s^{-1} at maximum, ion heating in the downstream area over 30 eV, and magnetic fluctuations mainly at 5–10 μs period. We succeeded in qualitatively reproducing chromospheric jets, but quantitatively, we still have some differences between observations and experiments such as in jet velocity, total energy, and wave frequency. Some of them can be explained by the scale gap between solar and laboratory plasma, while the others are probably due to the difference in microscopy and macroscopy, collisionality, and the degree of ionization, which have not been achieved in our experiment.

Key words: magnetic fields – magnetic reconnection – methods: laboratory – plasmas – Sun: activity – Sun: chromosphere

Online-only material: color figures

1. INTRODUCTION

Solar jets are ubiquitous phenomena both in the corona and the chromosphere. They sometimes show a cusp-like structure, which is thought to be evidence of magnetic reconnection and this reconnection between an emerging flux rope and the pre-existing coronal/chromospheric magnetic field may ubiquitously produce solar jets (e.g., Shibata et al. 1994; Yokoyama & Shibata 1995). Recently, the Solar Optical Telescope (SOT; Tsuneta et al. 2008; Suematsu et al. 2008; Ichimoto et al. 2008; Shimizu et al. 2008) on board Hinode (Kosugi et al. 2007) acquired a time series of Ca II H images in high spatial resolution, which revealed the fine structure of the sunspot magnetic field and the dynamic activities in the chromosphere, such as penumbral jets (Katsukawa et al. 2007), chromospheric anemone jets (Shibata et al. 2007; Nishizuka et al. 2008, 2011; Singh et al. 2011), and recurrent plasma ejections over the sunspot light bridge (Shimizu et al. 2009; Shimizu 2011). The vector magnetogram observations with Hinode also revealed for the first time that even component magnetic reconnection, i.e., reconnection between non-perfectly anti-parallel magnetic field lines, can be origins of jet activities. Especially in solar phenomena observed as evidence of component reconnection, chromospheric plasma ejections from sunspot light bridges are relatively well revealed by their photospheric magnetic configurations. These show current-carrying, highly twisted magnetic flux tubes trapped along the light bridge below a canopy structure of the umbral fields, forming the magnetic configuration favorable for magnetic reconnection at low altitudes (Shimizu et al. 2009). However, what differentiates the magnetic reconnection that occurs in this configuration from the perfectly anti-parallel magnetic reconnection, and whether it is possible to generate the dynamic ejections observed from this configuration, is not revealed.

Figure 1(a) shows the general magnetic configuration of solar jets from where magnetic reconnection originates between an emerging flux tube and the pre-existing vertical coronal or chromospheric magnetic field, as well as in sunspot light bridges. An emerging flux tube has a helical magnetic structure and interacts with the surrounding vertical field lines when it is lifted up by magnetic buoyancy. Two non-perfectly anti-parallel magnetic field lines of the emerging flux rope and the ambient corona/chromosphere reconnect on one side of the flux rope. This process has been modeled by three-dimensional magneto-hydrodynamic simulations (Moreno-Insertis et al. 2008; Pariat et al. 2010; Magara 2010). The helical magnetic configuration in the laboratory is called a spheromak, which has the toroidal and poloidal components of the magnetic field forming a twisted magnetic flux tube as well as the emerging flux rope in the solar atmosphere. Here, we note that the toroidal field (TF) is directed along the flux tube and the poloidal field (PF) circulates around the TF. Figure 1(b) shows an illustration of the magnetic reconnection between the spheromak and the newly emerged straight field lines induced by the center solenoid coil. In this case, helical field lines of the spheromak and the newly emerged straight field lines cross, causing component reconnection at the contact surface of the two.

Hinode observations have revealed high spatial magnetic configurations of chromospheric plasma ejections but they still are limited when it comes to revealing the fundamental physics of magnetic reconnection on a much smaller spatial scale and its three-dimensional structure, because the spatial resolution of SOT/Hinode is 150 km on the solar surface and only a single layer of the chromosphere is observable. Hinode also has difficulties observing real plasma flows with Doppler measurements, ion/electron temperatures, electrical resistivity, and magnetic fluctuations, as well as magneto-hydrodynamic
simulations of jets. On the other hand, laboratory plasma experiment has an advantage of directly measuring the plasma condition. In this paper, we reproduced the magnetic configuration of solar jets driven by an emerging flux rope and component reconnection by focusing on the similarity of the emerging flux and the spheromak. Then we investigated the details of the plasma ejections with direct measurements in the laboratory plasma experiment.

In Section 2, we explain the apparatus of the reconnection experiment of laboratory plasma and the method of measurements. In Section 3, we show experimental results such as reconnection jets, plasma heating, and wave generation. Finally, in Section 4, we discuss the experimental results and compare them with solar observations of chromospheric jets.

2. THE TS-4 EXPERIMENT

2.1. Apparatus of the TS-4 Experiment

The Tokyo Spheromak (TS) toroidal plasma merging experiments have been conducted to study plasma heating effects of magnetic reconnection since 1986 (e.g., Ono et al. 1993, 1997; Yamada et al. 1997). As shown in Figure 2, the instrument of the TS-4 device is composed of an axisymmetric toroidal vacuum vessel with length of 2.5 m and diameter of 2.0 m, and the two flux cores of the PF and TF coils for poloidal/toroidal flux inclusions (see more details in Kawamori & Ono 2005; Kawamori et al. 2007). The cylindrical coordinate is as follows: Z-axis in the axial direction, R-axis in the radial direction, and T-axis in the toroidal direction. TS-4 also contains a center solenoid coil called the OH coil (originally named Ohmic heating coil) along the Z-axis with a radius of 90 mm, the outside of which is filled with fully ionized plasma and has three kinds of probe arrays inserted into it: the two-dimensional magnetic field probe array, the magnetic fluctuation probe array, and the Mach probe. Locations of the probe arrays are overlaid on Figure 2. The vacuum vessel has a window through which the Doppler spectroscopy measurements are performed. With these instruments, we performed four different measurements simultaneously for the plasma diagnostics in the TS-4 device.

Figure 3 shows the schematic pictures of our experimental scenario. The time profiles of the electrical current induced in the TF, PF, and OH coils are shown in Figure 4. Initially the vacuum vessel is kept in a vacuum state that is less than 10^{-6} Torr and then filled with argon gas. The reasons for the selection of argon gas are reproducibility and emissivity compared with hydrogen. At first, argon plasma was fully ionized (more than 90%) and two toroidal plasmas with radius of 0.5 m were generated by the flux cores (Figure 3(a)). Two toroidal plasmas were merged together in the axial (Z) direction under magnetic compression provided by the pair of PF coils or acceleration coils (Figure 3(b)). The magnetic reconnection occurs at the contact point of the two toroidal plasmas, causing high-power plasma heating by magnetic reconnection. The merged toroidal plasma, i.e., spheromak, has a helical magnetic configuration with toroidal and poloidal components. Then we induced a new
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Figure 3. Illustration of light bridge reconnection in the double annular plasma configuration in the $R$–$Z$ plane. Thick line shows magnetic field lines and arrows show plasma flows. Gray color means dense plasma inside the spheromak. The large spheromak is formed through merging process (c) and reconnects with the new emerging straight magnetic field induced by the center solenoid (OH) coil (d).

PF by the OH coil anti-parallel to the PF of the spheromak (Figure 3(c)). The spheromak and the anti-parallel OH field were merged together in the radial ($R$) direction via magnetic reconnection. As the reconnection proceeds, the spheromak becomes increasingly smaller and the reconnection point moves upward (in positive the $R$-direction) under the control of the separation coils (Figure 3(d)).

The experimental parameters were selected to be similar to the chromospheric parameters in the Sun such as ion and electron temperatures $T_i = T_e = 10$ eV ($\sim 10^5$ K), electron density $n_e \sim 10^{14}$ cm$^{-3}$, and toroidal and poloidal magnetic fields $B_p/B_t = 400$ G/220 G at the surface of the spheromak (plasma beta $\beta \sim 0.06–0.24$). Here, we note that, with the above experimental parameters, the ion cyclotron frequency and gyroperiod are 50–150 kHz and 6–20 $\mu$s (100–300 G), ion Larmor radius 7 cm, local sound speed $7$ km s$^{-1}$ ($T = 10^5$ K), and ion Alfvén velocity $13$ km s$^{-1}$ ($B = 200$ G) for the argon ion we used, respectively. Therefore, in this experiment, we see microscopic phenomena around the reconnection region occurring in the solar chromosphere, which cannot be seen either in Hinode observations or in magnetohydrodynamic simulations.

2.2. TS-4 Diagnostics

The two sets of the $10 \times 9$ arrays of magnetic pickup coils were inserted into the $R$–$Z$ plane of the vessel to measure directly the two-dimensional magnetic field profile. Its spatial resolution is 80 mm in the radial direction and 90 or 135 mm in the axial direction. Its time resolution is 1 $\mu$s. The poloidal flux contours and current density profiles, based on axial symmetry assumption, were calculated from the measured $B_z$ and $B_t$ components of the two-dimensional magnetic field profiles. The current sheet was identified by the measured toroidal current density profile $J_t$ and the X-line structure. In more detail, the physical parameters $B_r$, $J_t$, and $E_t$ were calculated from $B_z$ using the following equations:

$$B_r(r, z) = -\frac{1}{2\pi r} \frac{\partial \Psi}{\partial z},$$

(1)

$$J_t(r, z) = \frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r} = -\frac{1}{2\pi r} \frac{\partial^2 \Psi}{\partial z^2} - \frac{\partial B_z}{\partial r},$$

(2)

$$E_t(r, z) = -\frac{1}{2\pi r} \frac{\partial \Psi}{\partial r},$$

(3)

where $\Psi(r, z, t) = \int_{r_{\text{min}}}^{r_{\text{max}}} 2\pi r' B_z \, dr'$ is the magnetic flux ($r_{\text{min}} = 92$ mm at the surface of the OH coil). Since the magnetic field is almost negligible in the current sheet, the effective resistivity is derived from $\eta = E_t/J_t$, although it is slightly affected by the magnetic flux inside the OH coil.
Figure 5. Snapshot images of (a) two toroidal argon plasmas merging and (b) merging of spheromak and OH field. Thick contours show magnetic field lines at regular intervals and thin contours are complementary to emphasize reconnecting field lines. The color bar indicates the toroidal current density measured by the two-dimensional magnetic probe array. (c) The radial profile of the $B_z$ component and (d) the toroidal current $J_t$ on the mid-plane.

An array of 27 magnetic pickup coils (Kuwahata et al. 2011) was also inserted into the mid-plane ($z = 0$), but with much shorter distances of 10 mm, to measure the one-dimensional magnetic fluctuation profile in the $R$-direction ($\delta B_r$). The magnetic fluctuation probe array is digitized by 200 M samplings s$^{-1}$ with the 8 bit analog to digital converters (ADCs). The integration of the measured $\delta B_z$ at the same location gives us the $B_z$ value, and the toroidal current density is calculated using $J_t = -\partial B_z/\partial r$, assuming that $B_r$ is negligible on the mid-plane.

The ion Doppler velocity $V_i$ and temperature $T_i$ diagnostics were performed by the fiber optic multi-channel imaging spectroscopy system (Tanabe et al. 2010). Twenty-three sets of multi-chord line spectra of Ar ii at 434.8 nm are collected to optical fibers. Each of them was collimated by an $f = 50$ mm and $F = 1.2$ camera lens and measured by ICCD imaging spectrometer with 256 pixel wavelength resolution (0.024 nm pixel$^{-1}$). At first, each Doppler width of the spectral line is calculated by using a Gaussian function fitting algorithm to plot the one-dimensional profile of $V_i$ and $T_i$ along the axial ($Z$) direction in the current sheet. Its spatial resolution is 20 mm in the axial direction, and its time resolution is 20 $\mu$s.

The one-dimensional ion velocity profile $V_i$ was also directly measured by the Mach probe array inserted along the current sheet near the OH coil at $r = 190$ mm. Its axial spatial resolution is 50 mm and its time resolution is 0.5 $\mu$s. The probe was used to directly measure the Mach number of the ion flow, which is calculated from the difference of the two current densities entering into the probe through the sheath, such as $\exp(KM) = J_{up}/J_{down}$. Since a paper on the $K$-value calibration for the Mach probe concluded $K = 2.0$–2.5 for SSX parameters ($T_e = 7$ eV, $T_i = 20$ eV; Zhang et al. 2011), we adopted $K = 2.5$ in this paper.

3. EXPERIMENTAL RESULTS

Figures 5(a) and 5(b) show the poloidal flux contours in the poloidal ($R-Z$) plane of two merging toroidal plasmas ($B_p = 400$ G, $B_t = 220$ G at the surface of the spheromak). These two toroidal plasmas were merged together during 380–400 $\mu$s (Figure 5(a) and illustrations in Figures 3(a)–(b)). Magnetic reconnection between the spheromak and the OH field occurred during 450–560 $\mu$s (Figure 5(b) and Figures 3(c)–(d)). At that time, the negative $J_t$ region (blue color in Figure 5(b)), which is a current sheet, was observed between the spheromak and the OH coil (92 mm $< r <$ 160 mm), and the effective resistivity enhancement was simultaneously observed (discussion in Section 4.2 and Figure 12). As shown in Figure 5(c) of the radial ($R$) profile of the $B_z$ component measured by the magnetic fluctuation probe array, the reconnection point between the spheromak and the OH field moved upward as the spheromak became increasing smaller. The reconnection point is located in the undetectable area below the wall of the vacuum vessel in the early phase, where reconnection occurs partially in vacuum and partially in plasma, leading to the morphology change of the global magnetic field accelerating the plasma through the sling-shot effect due to magnetic tension force. In the later
Figure 6. (a) The fanned line-of-sight directions of the fiber optic multi-channel imaging spectroscopy system overlaid on a snapshot image of the magnetic configuration of the spheromak at 535 $\mu$s with toroidal current density in color. (b) One-dimensional axial profiles of the ion Doppler velocity in the line-of-sight direction (almost $r$-direction) with compensation for toroidal velocity component and (c) ion Doppler temperature.

Figure 7. (a) The locations of the Mach probe shifted along the current sheet at $r = 190$ mm and $z = 100, 150, 200, 250, 300,$ and $400$ mm. (b) The axial ($Z$) profile of the ion velocity in the axial direction in units of Mach number ($C_s \sim 7$ km s$^{-1}$) at 420, 460, 500, and 540 $\mu$s.

phase, we directly observed the reconnection point with the two-dimensional magnetic probe array, when it moved upward as reconnection proceeded.

Figure 6 shows the axial ($Z$) profiles of ion velocities during 380–560 $\mu$s measured by the fiber optic multi-channel imaging spectroscopy system. To distinguish two-dimensional flow from the integrated line spectra in the line-of-sight direction, the system has three different views, from left-hand side, right-hand side, and just above the mid-plane. Their line-of-sight directions are shown in Figure 6(a). Since they are set to avoid the center solenoid coil, each spectrum contains toroidal velocity, but it is less than the 3 km s$^{-1}$ estimated from the bias velocity in view 3 and removed. Finally, the residual data of view 1 and 2 in Figure 6(b) show outflow velocities in the poloidal ($R-Z$) plane stereoscopically. Positive Doppler values mean ion flow in the direction opposite to each camera lens. Initially the plasma velocity was 0 km s$^{-1}$. Reconnection outflow was detected for 80 $\mu$s after 480 $\mu$s, during which ion flow was gradually accelerated to 3–4 km s$^{-1}$ in the line-of-sight direction (almost positive $R$-direction) at the fiber channel numbers 2, 7, and 13 in Figure 6(a) (near $z = \pm 400$ mm). The bi-directional outflow was observed around fiber channel numbers 4 and 10, which may correspond to the reconnection X-point. The reconnection outflow accelerated in time and with distance from the X-point.

Figure 7 shows the axial ($Z$) profiles of the ion velocity $V_i$ in the $Z$-direction during 380–560 $\mu$s, directly measured by the Mach probe at six positions, $z = 100, 150, 200, 250, 300,$ and $400$ mm, by turns. This is a complementary measurement for the previous Doppler spectroscopy. The ion velocity is presented in Mach number (local ion sound speed $C_s \sim 7$ km s$^{-1}$ for $T_i = 10$ eV). Before the reconnection, the ion velocity is detected to be zero. Positive velocity means rightward flow (outflow) from the mid-plane or the X-point. A reconnection X-point, i.e., the zero velocity point, existed between...
Figure 8. (a) The location of the magnetic fluctuation probe array overlaid on snapshot images of the plasma merging experiment with poloidal field contours and toroidal current in color. (b) Time slice image and (c) time plots of magnetic fluctuations $\delta B_z$ measured by the magnetic fluctuation probe array at $r = 90, 240, 380$ mm, whose positions are overlaid on (a) and (b).

(A color version of this figure is available in the online journal.)

$z = 100–170$ mm before $460 \, \mu s$ and then moved inward less than $z = 100$ mm as reconnection proceeded. The maximum velocity was $0.4 \, C_s$ (sound speed) at $z = 200$ mm. Inside the velocity peak, ion flow was accelerated proportional to the distance from the X-point. Outside $z = 200$ mm, ion velocity gradually decreased. These are consistent with the previous Doppler spectroscopy measurement.

Additionally we derived ion temperature from the Doppler spectroscopy measurements. Figure 6(c) shows the axial ($Z$) profile of the one-dimensional ion temperature $T_i$ during the merging of the spheromak and the OH field ($420–560$ $\mu s$). The initial ion temperature was uniformly $5–10$ eV. The ion temperature at the left downstream area was preliminary heated up to $13–25$ eV at first ($400–440$ $\mu s$). After that, the ion plasma was further heated up to $18–32$ eV ($440–480$ $\mu s$) at maximum. It is gradually cooled down to $15–20$ eV between $480–520 \, \mu s$ and then to $5–15$ eV between $520–560 \, \mu s$. The locations of the highest ion temperature and the largest ion velocity are almost the same in the left downstream area in view 1, though the other side in view 1 and both in view 2 were not.

Associated with magnetic reconnection, magnetic fluctuation of the $B_z$ component ($\delta B_z$) was also observed by the magnetic fluctuation probe array around the current sheet between $450–550 \, \mu s$. The locations of the fluctuation probe array and the corresponding two-dimensional poloidal flux contours measured by the two-dimensional magnetic probe array are shown in Figure 8(a). Figure 8(b) shows the time slice image of the magnetic fluctuations on the mid-plane, and Figure 8(c) shows three examples of $\delta B_z$ fluctuations. Since the current sheet and the reconnecting magnetic field lines are located in the axial ($Z$) direction, $\delta B_z$ fluctuations indicate longitudinal oscillation (magnetoacoustic sausage mode) or projected transverse oscillation with toroidal (guide) field to the poloidal ($R–Z$) plane. Here, we cannot distinguish standing waves from propagating waves with the current data. We applied wavelet analysis to these data. Details of the procedure are given by Torrence &
Compo (1998). Figure 9 displays the wavelet power spectra of magnetic fluctuations at different locations $r = 92, 112, 182$ mm on the mid-plane. In the wavelet spectrum diagrams, regions with 95% significance level are outlined. The power spectra show a peak in the period of 4–20 $\mu$s, in which there exists sub-structure at 5, 6, 10, 15–20, and 30 $\mu$s. The spectrum at 5 $\mu$s period also show two peaks at 440 $\mu$s and 480 $\mu$s in time variation (Figure 9(b)). The oscillation lasts for 90 $\mu$s, in which there are 16 periods for the shortest frequency. Here, we note that these oscillations are not affected by the magnetic fluctuations produced by the spheromak formation from 330 to 430, which is reduced by the smoothed long-term variation larger than 40 $\mu$s from the raw data, measured by the magnetic fluctuation probe array on the mid-plane at $r = 92, 112, 182$ mm (near the OH coil).

(A color version of this figure is available in the online journal.)

Figure 9. Wavelet power spectrum of magnetic fluctuations $\delta B_z$, which is reduced by the smoothed long-term variation larger than 40 $\mu$s from the raw data, measured by the magnetic fluctuation probe array on the mid-plane at $r = 92, 112, 182$ mm (near the OH coil).

4. DISCUSSION AND CONCLUSIONS

We reproduced the magnetic configuration of a twisted flux tube and chromospheric plasma ejections by component reconnection with laboratory experiment. Here, we focused on the similarity between magnetic configurations of the spheromak in the laboratory plasma and of the emerging flux rope in the solar atmosphere. We performed a two toroidal fully ionized argon plasma merging experiment, followed by magnetic reconnection driven by OH field emergence. We measured the two-dimensional magnetic field configuration, ion flow, ion temperature, and magnetic fluctuations at the same time during the reconnection process.

4.1. Acceleration Mechanism of Jets

Reconnection outflows were independently measured by the fiber optic multi-channel imaging spectroscopy system and the Mach probe. Both measurements show consistent results; the ion flow was accelerated proportional to the distance from the reconnection point and then decelerated by the accumulated magnetic flux at the outflow region. The maximum velocity in the line-of-sight direction ($R$-direction) $v_r$ was 4 km s$^{-1}$ from the Doppler measurement and the velocity in the axial (Z) direction $v_z$ was 0.4 $C_s$ (sound speed) at maximum from the Mach probe, giving 2.8 km s$^{-1}$ on the assumption that the local ion sound speed is 7 km s$^{-1}$. These values are about 40% of the local Alfvén velocity. In the later phase, plasma velocity near the mid-plane ($z = 100$ mm) increased as well as in the outer region (Figure 7(b)). At the same time, the reconnection point, that is, the transition of positive and negative (rightward and leftward) velocities, moved inward; it is located at $z = 150$ mm at 420 $\mu$s and moved to $z = 100$ mm at 460 $\mu$s and to less than 100 mm later. This may suggest two possible interpretations: one is that reconnection with a long current sheet transits to the X-type fast reconnection as shown in the illustration of Figure 10(a). The other one is that the reconnection point moves upward to the region detectable by the Mach probe, which is shown in Figure 10(b) for comparison.

Here we note that the current sheet thickness is 10 cm, while ion skin depth and ion Larmor radius are 14–70 cm and 7–14 cm (20 eV, 20 mT), respectively. Therefore, the current sheet thickness is comparable to or a little smaller than the ion skin depth or the ion Larmor radius. However, the electron and ion mean free paths are 1 cm, which are smaller than the current sheet thickness, so that the Hall current is not detected in our experiment. The reconnection rate is estimated to be $v_{in}/v_{out} = 0.13–0.33$ for $v_{in} = 0.5–1.0$ km s$^{-1}$ and $v_{out} = 3–4$ km s$^{-1}$, respectively, while the Sweet–Parker reconnection rate is $1/R_m^{1/2} = 0.05–0.1$ for $R_m = 100–400$. Hence, the reconnection in our experiment is slightly faster than the Sweet–Parker reconnection. Here, we can say that collisionality suppresses the Hall effect and leads to the Sweet–Parker reconnection or slightly faster reconnection, though the physical mechanism driving reconnection faster without the Hall effect is not revealed.

Generally, the plasma flow is accelerated by plasma pressure and magnetic tension force. However, no enhancements of the temperature and density of ions and electrons were detected at the center of the current sheet in this experiment, so it is expected that the plasma flow was not accelerated by plasma pressure but is magnetically accelerated. Figure 11(a) shows the Lorentz force in the Z-direction $(J \times B)_z = J_zB_z$. Near the
mid-plane ($-300 \text{ mm} < z < 300 \text{ mm}$), the Lorentz force plays a role in accelerating the plasma outward in opposite directions from the mid-plane ($z = 0$). Beyond 300 mm from the mid-plane, the Lorentz force changes to a deceleration force due to the surrounding closed magnetic field. The absolute value of the Lorentz force increases in time and spatially in the axial and radial directions. If we assume the average value of the Lorentz force $(J \times B)_z = 10 \text{ N}$ calculated from Figure 11(a), the acceleration is estimated to be $1.6 \times 10^3 \text{ km s}^{-2}$ and the accelerated velocity is $15.9 \text{ km s}^{-1}$ with the acceleration time of 100 $\mu$s. This is comparable to, but slightly larger than, the measured values.

Next we show the moving velocity of the magnetic field lines at $r = 146 \text{ mm}$ in Figures 11(b)–(d) in order to compare with the measured ion flow. It is estimated from Ohm’s law with the two-dimensional magnetic probe data that $B = (B_r, B_t, B_z)$ and $E = (0, E_t, 0)$. The three components of the magnetic field velocity are given by

$$v_\perp = \frac{E \times B}{|B|^2} = \left( \frac{E_t B_z}{|B|^2}, 0, -\frac{E_t B_r}{|B|^2} \right),$$

which is derived from Ohm’s law, $E = -v \times B$. The $z$-component of $v_\perp$ in Figure 11(b) indicates the outward velocity of reconnected filed lines in the axial ($Z$) direction, where a positive (negative) value means rightward (leftward) velocity. Similarly, the $r$-component of $v_\perp$ in Figure 11(c) indicates the inward velocity of the field lines to the current sheet in the radial ($R$) direction, where a negative value means the inflow to the current sheet. Figure 11(d) shows the absolute value of the field line velocity. It shows the velocity peak at around 3–4 km s$^{-1}$ near $z = 200 \text{ mm}$. We can also find that the velocity peak moves...
inward from 420 μs to 540 μs, consistent with the Mach probe measurement of the ion flow, though argon gas is not completely frozen into the magnetic field lines.

Our experimental results show the ion velocity with both axial and radial components, which means that reconnection outflow is oblique against the surrounding stratified (vertical) magnetic field lines. This is consistent with the fact that magnetic tension force works obliquely to the stratified field with the angle of 45° as shown in Figure 5(b). However, in solar observations, it appears that plasma ejections over the light bridge occur along the vertical magnetic field lines. This is probably because the reconnection outflow is redirected to the parallel direction of the surrounding straight field lines after the collision of the plasma flow and the magnetic field lines. Therefore, even in a laboratory experiment, it would be reproduced in a much larger spatial scale where magnetohydrodynamic behavior becomes dominant.

4.2. Relationship Among Jet, Heating, and Wave Generation

Figure 12(a) shows the relationship between the resistivity enhancement and the outflow acceleration in time. The effective resistivity is measured at \( r = 119 \) mm on the mid-plane (\( z = 0 \) mm) and peaks at 450–480 μs. The outflow velocities at two different locations, \( z = 200 \) mm and 300 mm, are overlaid on it. The acceleration of reconnection outflow occurs just after the enhancement of effective resistivity. The peak of the outflow velocity at \( z = 300 \) mm is earlier and smaller than the one at \( z = 200 \) mm. Time variations of the ion temperature measured by the Doppler spectroscopy measurement with fiber channel 1, roughly at \( z = -300 \) mm and \( r = 90–200 \) mm, and the power spectrum of magnetic fluctuations with 5 μs periods, which is overlaid by ion temperature observed by the Doppler spectroscopy measurement.

**Figure 12.** (a) Time variation of the effective resistivity \( \eta = E_\theta / J_\theta \) and the ion velocities at \( r = 190 \) mm and \( z = 200 \) and 300 mm. (b) Time variation of power spectra of magnetic fluctuations with 5 μs periods, which is overlaid by ion temperature observed by the Doppler spectroscopy measurement.

Ion heating occurred in the left downstream area close to the surrounding closed magnetic field. The ion temperature increased to 20–30 eV. The heating by reconnection is expected to be \( T_0/\beta \) in magnetohydrodynamic theory, where \( T_0 \) is the initial temperature and \( \beta \) is the plasma beta (Yokoyama & Shibata 1995). Assuming \( \beta = 0.25 \), heating occurs from 10 eV to 40 eV. This is comparable to the measurement. The fact that ion heating occurs at the edge of the downstream area is consistent with the previous merging experiment (Ono et al. 2011), though the distance of the heating spot from the X-point is larger (approximately four times). This is probably because the distance from the X-point to the obstacle may determine the heating spot. Ono et al. (2011) suggested ion heating by the fast shock in the downstream area with laboratory experiments, but the fast shock may not be formed in this experiment because the measured Mach number is always less than unity. Rather it is interesting to see that the enhancement of magnetic resistivity and waves are in association with ion temperature enhancement.

The locations of enhanced resistivity and hot ion spot is different from each other, so the association of ion heating and waves may indicate some physical relationship among them. In solar observations, it is impossible to detect μs order waves. However, this experimental result may suggest that such high frequency waves are generated through the magnetic reconnection process and contribute to the ion (and electron) heating.

Figures 13 shows the different magnetic configurations of the simple spheromak merging experiment and the OH field merging experiment. The former experiment confines hot plasma at the center of the spheromak with closed field lines, but the latter does not. In the OH field merging experiment, the hot plasma spot is not maintained for a long time and diffused along the surrounding straight open magnetic field lines. This would also affect the wave generation associated with magnetic reconnection.

### 4.3. Energy Estimation of Magnetic Reconnection

Experimental measurements of ion temperature and velocity enable us to estimate thermal and kinetic energies converted from the released magnetic energy. Assuming plasma density \( n = 10^{14} \) cm\(^{-3}\), the thermal energy is \( E_{th} = \frac{1}{2} k_n T V = 1.1 \times 10^7 \text{ erg} \) (\( V = 3.8 \times 10^4 \text{ cm}^3 \) and \( T_i = 30 \text{ eV} \)) and the kinetic energy is \( E_{kin} = \frac{1}{2} \rho V n m_i v_i^2 / 2 = 3.2 \times 10^8 \text{ erg} \) (\( V = 2.3 \times 10^4 \text{ cm}^3 \) and \( v_i = 4 \text{ km s}^{-1} \)), leading to the total converted energy 1.1 \times 10^7 \text{ erg}. It seems that kinetic energy is much smaller than thermal energy converted from magnetic energy in this experiment.

On the other hand, the reconnection rate of the total magnetic flux \( \partial \Psi / \partial t \) is of the order of \((2–3) \times 10^{14} \text{ Mx s}^{-1}\). By assuming two-dimensional steady magnetic reconnection, the released magnetic energy can be estimated at the Poynting flux entering from both sides into the reconnecting region using the relation,

\[
\frac{dE_{mag}}{dt} = 2 \frac{B^2}{4 \pi} v_{in} A,
\]

where \( dE_{mag}/dt \) is the magnetic energy release rate due to magnetic reconnection, \( B \) is the magnetic flux density in the spheromak, \( v_{in} \) is an inflow velocity to the reconnection site, and \( A \) is the surface area of the current sheet (\( A = 2 \pi r L_z = 2500 \text{ cm}^2 \); for \( r = 10 \text{ cm} \), \( L_z = 40 \text{ cm} \)). Since we cannot know the actual inflow velocity \( v_{in} \), we use a perpendicular velocity to the magnetic field lines assuming zero resistivity outside the current sheet, such that \( (v_\perp) = E_i B_\perp / |B^2| \) as
an assumption. Figure 11(c) shows the \(v_\perp\) profile in the Z-direction at \(r = 146\) mm, thus \(v_\perp = 0.5–1.0\) km s\(^{-1}\) and the resulting energy release rate \(dE_{\text{mag}}/dt = 6 \times 10^{12}\) erg s\(^{-1}\), with the total energy release \(3 \times 10^9\) erg for the duration of magnetic reconnection, 50 \(\mu\)s. These are comparable to the estimated total of the thermal and kinetic energies, \(10^8\) erg.

As for the energy gap between laboratory experiments \((10^9–10^{10}\) erg) and solar observations \((10^{24}\) erg), it would be explained by the scale gap between laboratory and solar plasmas, because stored magnetic energy \(E_{\text{mag}} \propto B^2L^2\) under the condition that \(B\) is constant. Since the spatial scale of solar plasma is 4–5 orders larger than laboratory plasma, stored energy is self-similarly enlarged to \(E_{\text{mag, solar}} = 10^{12–15} E_{\text{mag, lab}} \sim 10^{20–1024}\) erg, corresponding to the nanoflare energy regime \(\sim 10^{20–1024}\) erg, because stored magnetic energy is self-similarly enlarged to \(E_{\text{mag}} \propto B^2L^2\) under the condition that \(B\) is constant. Since the spatial scale of solar plasma is 4–5 orders larger than laboratory plasma, stored energy is self-similarly enlarged to \(E_{\text{mag, solar}} = 10^{12–15} E_{\text{mag, lab}} \sim 10^{20–1024}\) erg, corresponding to the nanoflare energy regime of solar observations, that is, chromospheric jets. Similarly, the reconnection timescale is determined by \(\tau_{\text{rec}} = \sqrt{\tau_{\text{A}t_{\text{d}}} \propto L^{3/2}}\), where the Alfvén timescale is \(\tau_{\text{A}} = 4.5\) \(\mu\)s and the diffusion timescale is \(\tau_{\text{d}} = 316\) \(\mu\)s by assuming the current sheet width \(L = 10\) cm in laboratory experiment, and then \(\tau_{\text{rec, lab}} = 38\) \(\mu\)s. The reconnection timescale in the solar atmosphere would be, therefore, self-similarly enlarged to \(\tau_{\text{rec, solar}} = 10^6–10^7 \tau_{\text{rec, lab}} \sim 38–1200\) s. This is also comparable to solar observations (Nishizuka et al. 2011; Singh et al. 2011).

As mentioned in Section 4.1, our experimental results are in the regime of microscopic or marginally meso scale, so that we cannot directly predict macroscopic MHD phenomena driven by magnetic reconnection in solar atmosphere from these experimental results. Nevertheless, the essential reconnection process should be included in the microscopic regime if we suppose a Sweet–Parker-like diffusion region. Thus the microscopic properties, such as reconnect rate, anomalous resistivity, and inflow/outflow velocity patterns, observed in this experiment could be compared quantitatively with those in the solar observations to see fundamental behaviors of magnetic reconnection.

Numerical simulations would be helpful to connect the microscopic experimental results with the macroscopic solar observations. Global MHD simulation including key reconnection microphysics based on the experimental results will be an interesting future work under the framework of laboratory and solar observation collaboration.

4.4. Wave Mode and Energy Flux

Magnetic fluctuations of the \(B_z\) component, i.e., waves, were detected in the current sheet (negative \(J_r\) region) during magnetic reconnection. They show multiple frequencies, mainly at \(5–6\) \(\mu\)s and \(10\) \(\mu\)s. Since the measured frequencies are lower than the lower hybrid (LH) frequency \(\left(f_{\text{LH}} = \sqrt{f_{ci} f_{ce}} = 2\right.\) MHz, \(f_{\text{LH}}^{-1} = 0.5\) \(\mu\)s) and rather close to the ion cyclotron frequency \(\left(f_{ci} = 50–150\right)\) kHz, \(f_{ci}^{-1} = 6–20\) \(\mu\)s, the measured fluctuations may not be explained by the LH instability (Bale et al. 2002; Carter et al. 2002) nor the modified two-fluid instability (Ji et al. 2004), but by some kind of the drift (kink) instability (Zhu & Winglee 1996; Kuwahata et al. 2011) or shear Alfvén mode, though it cannot be identified with the current data set. If we consider the oscillation driven by the restoring magnetic force due to magnetic reconnection, the Alfvén timescale determines the oscillation time period, that is, \(\tau_A = L/V_A = 10\) \(\mu\)s \((L/25\) cm \((V_A/22\) km s\(^{-1}\))\(^{-1}\), assuming the scale length to be the half-radius of the spheromak (25 cm). This is comparable to the measured frequencies. Furthermore, if we consider Alfvén waves generated by magnetic reconnection in the solar atmosphere, the wave period would be enlarged to \(\tau_A, \text{ solar} = 10^6–10^7 \tau_A, \text{ lab} = 10–100\) s by considering the scale gap between the laboratory and solar plasmas. This is comparable to the solar observations of wave periods of 200 s as observed in solar chromospheric jets (Nishizuka et al. 2008; Liu et al. 2009), an X-ray jet (Cirtain et al. 2007), and spicules (De Pontieu et al. 2007; Okamoto & De Pontieu 2011).

The energy fluxes carried by the transverse (Alfvén) wave along the guide field in the current sheet in the toroidal and axial directions are described by

\[
F_{A,t} = \frac{1}{4\pi} \left[ -\delta B_z \delta v_z B_t - \delta B_t \delta v_z B_z \right] \tag{6}
\]

\[
F_{A,z} = \frac{1}{4\pi} \left[ -\delta B_t \delta v_z B_z - \delta B_z \delta v_z B_z \right]. \tag{7}
\]

Here, we assume that magnetic fluctuations occur only in the two-dimensional \(Z-T\) plane, i.e., \(\delta B_z = \delta v_z = 0\), resulting in the relationships \(\delta v_z = (\delta B_z/B_t) v_z\) and \(\delta v_z = (\delta B_t/B_z) v_z\). Since the fluctuations occur perpendicular to the guide field, we...
derive $\delta B_z = -(B_z / B_t) \delta B_t$. Furthermore, by using equations such as $(\delta B_z / \delta B_t) = (\delta v_t / \delta v_z)$ and $(v_t / B_t) = (v_z / B_z)$, we estimate the energy fluxes in the toroidal direction $F_{A,t} \sim 7 \times 10^6$ erg cm$^{-2}$ s$^{-1}$ and in the axial direction $F_{A,z} \sim 3 \times 10^7$ erg cm$^{-2}$ s$^{-1}$, respectively. This leads to the total energy flux of $3.8 \times 10^7$ erg cm$^{-2}$ s$^{-1}$ and the total energy of $3 \times 10^7$ erg for the duration of reconnection, 50 $\mu$s. This is 1%–10% of the estimated released magnetic energy and comparable to the previous expectations from numerical simulations of 3% in Yokoyama (1998) and 40% at maximum in Kigure et al. (2010).

### 4.5. Conclusions

We experimentally investigated fundamental physics of chromospheric jets observed in the solar atmosphere and succeeded in qualitatively reproducing the jets with component magnetic reconnection. As an advantage of laboratory experiments, we could directly measure magnetic field strength in the two-dimensional plane, plasma (ion) flows, ion temperature, effective magnetic resistivity, and high frequency waves in association with magnetic reconnection. These measurements are impossible in solar telescope observations and partly in magnetohydrodynamic simulations.

However, on the other hand, qualitatively we found some differences between the laboratory experiment and the solar observations. For example, jet velocity is much smaller than Alfvén velocity (40%) in our laboratory experiment, while in solar observations it is comparable to each other. The direction of the reconnection jet in laboratory experiment is oblique to the direction parallel to the surrounding straight magnetic field lines, while in the solar atmosphere it looks parallel to the surrounding vertical magnetic field. The total release energy, the reconnection timescale, and the wave frequency are also different in laboratory and solar plasmas by several orders.

Here, it is useful to consider the differences between microscopic and macroscopic scales, collisionality (collisional and collisionless), which may come from not only the instrumental size but also the selection of argon gas, and the degrees of ionization (fully ionized and partially ionized) in solar chromospheric and laboratory plasmas. The reasons for the selection of argon gas are reproductivity and emissivity compared with hydrogen, but it makes the ion mass and Larmor radius larger than hydrogen’s which is the majority of gas in the solar atmosphere. We expect that MHD scale physics may play an important role in accelerating reconnection jet to the local Alfvén speed. This would be impossible to investigate in relatively small scale laboratory experiments compared with the solar atmosphere. The scale gap between laboratory and solar plasmas may also explain the differences of the release energy, the reconnection timescale, and the wave frequency by the scaling law. Furthermore, recent studies of chromospheric anemone jets suggest that neutral particles in partially ionized plasma, such as chromospheric plasma, may drive fast reconnection (Nishizuka et al. 2011; Singh et al. 2011), though plasma is fully ionized enough during the reconnection event in our current experiment that it seems that the effect of partial ionization does not appear. The experiment with partially ionized hydrogen plasma is an interesting topic for future work.

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