Laboratory observation of plasmoid-dominated magnetic reconnection in hybrid collisional-collisionless regime

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Magnetic reconnection, breaking and reorganization of magnetic field topology, is a fundamental process for rapid release of magnetic energy into plasmas that occurs pervasively throughout the universe. In natural circumstances, the plasma properties on either side of the reconnection layer are almost asymmetric, in particular for the collision rates that critically determine the underlying reconnection mechanism. To date, all laboratory experiments on magnetic reconnections have been limited to purely collisional or collisionless regimes. Here, we report a well-designed experimental investigation on magnetic reconnections in a hybrid collisional-collisionless regime by interactions between laser-ablated copper and plastic plasmas. We directly observe the topology evolutions of the whole process of this asymmetric magnetic reconnection by highly-resolved proton radiography. Through this, we show that the growth rate of tearing instability in such a hybrid regime is still extremely large, resulting in rapid formation of multiple plasmoids and generation of plasmoid-dominated current sheet.

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Magnetic reconnection is a physical process occurring nearly anywhere there’s plasma, in which the magnetic topology is rearranged and magnetic energy is converted to kinetic energy, thermal energy, and particle acceleration\textsuperscript{12}. As plasma makes up the stars and ninety-nine percent of the visible universe, magnetic reconnection is ubiquitous and plays a key role in many energetic events throughout the whole universe such as magnetospheric substorms, coronal mass ejection, solar flares\textsuperscript{3} and so on. However, due to the vastly different plasma properties and spatiotemporal scales, it is hard to give a universal model for describing the mechanism of magnetic reconnection.

A key element of magnetic reconnection is the reconnection electric field $E_{\text{rec}}$, which plays a pivotal role in both energy conversion and production of energetic particles by doing work on particles. The normalized reconnection electric field is also employed to represent the reconnection rate. Theoretical and simulation studies have shown that $E_{\text{rec}}$ depends heavily on the plasma properties\textsuperscript{4}, in particular, the collision rate as a combination of plasma density and temperature. In the strongly collisional regime, such as magnetic reconnections in solar/stellar photosphere and chromosphere\textsuperscript{5}, $E_{\text{rec}}$ is induced by the plasma resistivity as described by the Sweet-Parker model\textsuperscript{6,7}, which, however, leads to a rather slow reconnection with low reconnection rate. By contrast, in the weakly collisional or collisionless regime, such as those occurring in magnetopause\textsuperscript{8} and magnetotail\textsuperscript{9}, $E_{\text{rec}}$ is contributed mainly by the off-diagonal (nongyrotropic) component of the electron pressure tensor\textsuperscript{10,11}, resulting in a fast reconnection that is independent of the plasma collision rate.

However, for some natural circumstances in the universe, a large class of magnetic reconnection lies in a hybrid regime where the reconnection plasmas have asymmetric collision rates with one side in a strongly-collisional state and the other in a weakly-collisional or collisionless state. One of the most typical scenarios for such hybrid collisional-collisionless magnetic reconnection occurs in the solar/stellar atmosphere\textsuperscript{12}, see Fig. 1a, when the cool (electron temperature $T_e \sim 10^4$ K), dense (plasma density $n_e \sim 10^{11}$ cm$^{-3}$) filaments erupting from the chromosphere collide with the hot ($T_e \sim 10^6$ K), tenuous ($n_e \sim 10^8$ cm$^{-3}$) loops in the corona, which has been directly observed by the Solar Dynamics Observatory (SDO)\textsuperscript{13}. As we know, the collisional mean free path $\lambda_{\text{ci}} \propto T_e^n n_e^{-1}$, therefore, the plasma in the filaments is highly collisional while that in the coronal loops is collisionless. Such hybrid magnetic reconnection may also occur when the magnetic fields in the dense accretion disk collide with those in the tenuous interstellar medium.

So far, most laboratory experiments\textsuperscript{14-18} of magnetic reconnection are focused on the purely collisional and/or collisionless regimes, in particular, relativistic\textsuperscript{19} or electron-dominated\textsuperscript{20} reconnection is almost always collisionless. The reconnection experiment\textsuperscript{21,22} by laser-driven colliding plasmas with asymmetric flow velocities arising from the delay between laser drives are carried out, where, however, almost no impacts on the reconnection dynamics have been observed because the reconnection plasmas are both still purely collisionless. Although the transition from collisional to collisionless through the current sheet thinning, has been discussed theoretically\textsuperscript{23,24}, the effect of asymmetry therein remains unclear. In addition, to date, the evolutions of magnetic topologies for the whole process of the plasmoid-dominated magnetic reconnections\textsuperscript{25,26} including the growth of tearing instabilities\textsuperscript{27} and the formation of multiple plasmoids\textsuperscript{28,29} have never been directly observed, where only indirect measurements through the interferometry\textsuperscript{30,31} have been given.

Here, we report result of the first experiment, to the best of our knowledge, on asymmetric magnetic reconnections in the hybrid collisional-collisionless regime by colliding of laser-ablated high-Z copper (Cu) and low-Z plastic (CH) plasmas. It shows that the growth rate of the tearing instability in such a hybrid regime is still extremely large, resulting in rapid formation of multiple plasmoids. Combined with numerical simulations, this rate is lower than that in the purely collisionless regime but much higher than the collisional case (where only single X-point forms). Using the temporally and spatially highly-resolved proton radiography, we provide the direct measurement of magnetic topology evolutions for the whole process of such plasmoid-dominated magnetic reconnection, so that the specific reconnection dynamics including growth of the tearing instability and formation of multiple plasmoids are well characterized. The experimental results are well reproduced and explained by self-consistently combining the radiation-magnetohydrodynamic (RMHD) and particle-in-cell (PIC) simulations as well as the proton radiography iterative inversion algorithm. Physically, in the hybrid magnetic reconnection, the reconnection electric field show much distinct feature, which is large and grows fast at the collisionless plasma side induced by the non-gyrotropic component of the electron pressure tensor, whereas smaller and more slowly at the collisional side induced by only the resistivity.

Fig. 1 Hybrid collisional-collisionless magnetic reconnection configurations and experimental set-up. a Magnetic reconnection in the hybrid regime between the collisional solar filaments and the nearby collisionless coronal loops. b Setup for the experiment on magnetic reconnection in the hybrid collisional-collisionless regime, which is achieved by irradiation of Cu (yellow) and CH (C\textsubscript{2}H\textsubscript{2}, green) foil targets respectively with long ns laser pulses synchronously. Proton radiography is set up along the face-on (−z–axis) direction for probing the magnetic field topology changes during the reconnection process, where the high-quality proton beam is generated from a tantalum foil target driven by the relativistic ps laser pulse, see Methods.
Results

Experimental setup. The hybrid magnetic reconnection experiments are carried out on the ShenGuang II Upgrade (SG-II-U) laser facility that has 8 ns pulses and 1 relativistic ps pulse. Figure 1b shows a diagram of the experimental setup, where the asymmetric collisional-collisionless reconnection is achieved by irradiation of Cu and CH foil targets respectively with long ns laser pulses synchronously. The ablated low-Z CH plasma is in the collisionless state, while the high-Z Cu plasma is in the collisional state, due to their different ionization charge states. These two plasmas expand and collide with each other, forming the magnetic reconnection in the hybrid regime, because both of them advect the self-generated Biermann magnetic fields together, as also shown in 1b (see the density maps and field lines). In order to balance the aspect ratio of the current sheet L/δ and the relative velocity of the plasma bubbles, the distance between the two focal spots is appropriately set to be 1.8 mm. The temporally and spatially highly-resolved proton radiography is set up along the face-on (−z-axis) direction for probing the magnetic field topology changes during the reconnecting process, where the high-quality proton beam is generated by target normal sheath acceleration from a tantalum foil target driven by the relativistic ps laser pulse. For improving the quality of the proton beam, we optimized the thickness of the backlight target to 20 μm, meanwhile, for reducing the scattering of protons, a 0.5 mm gap was left between the Cu and CH targets, and the commonly used mesh-grid has been removed to reduce blurring. The static radiography images clearly show that the proton beam is of high quality with almost uniform distributions, where the cut-off energy exceeds 30 MeV, see Supplementary Note 1 and Fig. 1. For protons with energy of typically 13.5 MeV, we estimate the time for them to pass through the reconnection region is about 20 ps, far less than the characteristic plasma evolution time (generally ~ ns), so that the transient radiography can be guaranteed.

Features of self-generated Biermann magnetic fields. To have an intuitive understanding of the self-generated Biermann magnetic fields in laser-driven expanding plasmas, we firstly take proton radiography for a single CH plasma bubble. The radiography images are shown in Fig. 2a, b at time t = 0.7 and 1.0 ns, respectively, which correspond to the radiography protons of 13.5 and 7.7 MeV. We see that the protons are deflected into the inside of the plasma bubble and a clear low-dose ring structure is formed on the periphery of the plasma bubble, which can be regarded as the direct evidence for generation of a toroidal, clockwise Biermann magnetic field. Note that, if it is a radial electric field, the protons should be deflected outside the plasma bubble32. Further, comparing 2a, b, we can also estimate the plasma expansion velocity parallel to the target surface is about 700 km s−133, as about 2.0 c0, where c0 = (γm0Tc/m)1/2 is the ion sound speed. Similar radiography images of laser-ablated Cu plasmas are also obtained, by which we estimate that its expansion velocity is on the same order due to the similar charge-to-mass ratio Z/μ. These self-generated Biermann magnetic field topologies are also verified by our three-dimensional (3D) synchronous proton radiography experiment (unpublished).

To extract more quantitative information from the radiographies, we use the inverse field-reconstruction code “PROBLEM”34 to recover the path-integrated magnetic fields ψ, see Methods. Reconstructed ψ for the dashed-box region in Fig. 2a and b are shown in 2c and d respectively, which further confirms the existences of toroidal magnetic fields in expanding plasmas (see red dashed curves). The value of ψ is about 4.0 T·mm, from which we can estimate the average field strength about >10 T. This is in good consistence with the estimation under paraxial approximation, where the path-integrated magnetic field ψ is estimated35,21,22 as

$$\psi(T \cdot \text{mm}) \approx \frac{\int_0^d Bdz \approx 0.1445 \sqrt{E_p(\text{MeV})}}{L(\text{mm})},$$

where w and L are respectively the width of the low-dose ring and the distance from the plasma to the RCF stack, and E_p is the proton energy. Assuming w~500 μm, E_p~13.5 MeV and L~50 mm for CH plasma in 2a, the magnetic field is roughly estimated as ψ~5.3 T·mm, and the field in 2b at t = 1.0 ns is about 7.6 T·mm.

Hybrid collisional-collisionless magnetic reconnection: experimental results. The proton radiography results of the magnetic field topologies at various times in Fig. 3a–d provide direct picture of the whole process for the magnetic reconnection in this asymmetric regime. At time t = 0.3 ns (Fig. 3a), we see that the toroidal Biermann magnetic field still has not sufficiently developed and is not prominent, where some small-scale jet-like proton accumulations exist possibly due to the filamentary magnetic field arising from escaping of hot electrons35. At time 1.0 ns (Fig. 3b), two low-dose rings (marked by the blue dashed lines) form at respectively collisionless CH and collisional Cu plasmas, which indicate the toroidal Biermann magnetic fields form, similar to those in Fig. 2a, b. We also see that the two magnetic fields already start to touch each other, consistent with the above estimations of their expansion velocities. Further, we see that more protons accumulate inside the Cu plasma bubbles than that of CH, indicating a stronger self-generated magnetic field, which is attributed to a steeper temperature gradient VTc of Cu plasmas, see Supplementary Note 2 and Fig. 2. Also, the sharper proton accumulation radiography in CH plasmas may benefit from the uniform drive laser focal spot in our experiment, rather than the Gaussian one in Cu plasmas.

At later time t = 1.5 ns [3(c)], both Cu and CH plasmas continue to flow in, and as a result, the anti-parallel magnetic
fields are strongly squeezed in their colliding region forming a reconnection current layer. Correspondingly, the proton radiography image (Fig. 3c) shows that two low-dose rings merge into a long and narrow ribbon with length $\Delta x_{\text{exp}} \sim 1.9$ mm and width $\Delta y_{\text{exp}} \sim 0.3$ mm. Almost all protons are deflected out of this narrow ribbon region indicating that rather strong magnetic fields exist locally, and the Y-shaped opening ends at both side of the ribbon region imply that the magnetic fields in Cu and CH plasmas begin to separate. Finally and more importantly at time $t = 1.8$ ns [3(d)], we see that the uniform low-dose ribbon is disturbed, and several high-dose fine filaments appear (marked by the red-dashed circles), which means that protons pass through without significant deflection. In other words, it means that the magnetic fields are dissipated at these fine filamentary regions, which is the key evidence for the occurrence of magnetic reconnection.

To more accurately reflect the change of the magnetic field topology, the reconstructed path-integrated magnetic fields $\psi$ and the corresponding vector potential $A_z$ (see field lines) are shown in Fig. 3f-h, see Methods. They clearly show that the two toroidal magnetic fields [see 3f] are piled up together, forming a narrow reconnection layer dominated by only the anti-parallel $B_z$ component [see Fig. 3g], the field strength at the center tends to zero. As shown in Fig. 3e for the profile of $\psi$ along y-axis, we see that the asymmetry of the plasma properties results in the asymmetric magnetic flux (blue curve), which is stronger in Cu ($y > 0$) than CH ($y < 0$). And at later time, the current sheet on the side of the Cu plasma is obviously widened than that in CH plasmas (red curve), which may be the result of the magnetic diffusion caused by the strong collision effect. Using the Ampere’s law $\mathbf{J} = \nabla \times \mathbf{B}/\mu_0$, it is estimated that the width of the current sheet (peak to peak) is about $2\delta_{\text{exp}} \sim 150 \mu m$, which is much smaller than the length $2L \sim 1.9$ mm. For such a long and narrow current sheet, the tearing instability occurs and develops rapidly, resulting in formation of multiple plasmoids, which are shown clearly in 3(h) by the red contours, also corresponding to the high-dose filaments in the radiography image 3d. Further, we see that there are still lots of un-reconnected magnetic fluxes on the outside of the fragmented current sheet, which may be due to the inefficient plasmoid ejection (because of high $\beta$) prevents further inflow of upstream magnetic fields. Compared with other published CH-CH reconnections, the current sheet in our experiment is more unstable to the tearing instability. In view of the above radiography results, we conclude that we have directly observed the growth of the tearing instability and formation of multiple plasmoids as well as the whole reconnection dynamics in the plasmoid-dominated magnetic reconnection.

Hybrid collisional-collisionless magnetic reconnection: simulation results. The above experimental results are reproduced and explained by a self-consistent combination of RMHD and PIC simulations as well as the proton radiography iterative inversion algorithm. As mentioned, magnetic reconnection is a rapid process of global magnetic topological self-organization triggered by local reconnection points, which depends critically on the plasma states. Before two plasma interactions, the laser-ablated plasma expansion dynamics is majorly governed by RMHD. Therefore, we firstly run the RMHD simulations with the ”FLASH” code to obtain the basic plasma parameters as the initial condition for the following PIC simulations that can describe the interaction and reconnection dynamics of two plasmas. The expanding Cu and CH plasma parameters obtained from RMHD simulations are summarized in Table 1a, where the electron density $n_e$, temperature $T_e$, flow velocity $v$ and magnetic field strength $B$ are all taken for those at the periphery of each plasma bubble.
Table 1 Plasma parameters obtained from radiation-magnetohydrodynamic (RMHD) and following self-consistent particle-in-cell (PIC) simulations.

| Plasma Properties | RMHD | PIC |
|-------------------|------|-----|
| $n_e$ ($10^{18}$ cm$^{-3}$) | 2.5 ± 1.0 | 8.0 ± 3.0 |
| $T_e$ (keV) | 1.5 ± 0.2 | 1.1 ± 0.1 |
| $v_{\text{A}}$ (km/s) | 20 ± 2 | 3.5 |
| $P_\text{th}/P_\text{mag}$ | 40 ± 10 | 25 ± 10 |
| $P_\text{ram}/P_\text{mag}$ | 800 ± 100 | 1000 ± 100 |
| $\beta$ | 1.0 ± 0.2 | 5.7 ± 1.0 |
| $\beta_{\text{ram}}$ | 6.7 ± 1.0 | 50 ± 10 |
| $\delta_{\lambda}$ | 8000 ± 2000 | 12000 ± 3000 |
| $\delta_{\text{opt}}$ | 3000 ± 500 | 12000 ± 3000 |

(a) The expanding Cu and CH plasma parameters at $t = 0.8$ ns obtained from the three-dimensional (3D) RMHD simulations, which are used as the initial condition for the following PIC simulations after self-similar scaling. (b) The plasma parameters inside the compressed reconnection layer (current sheet) of respectively Cu and CH sides at $t = 1.3$ ns obtained from PIC simulations, which are exactly the plasma states for magnetic reconnection. The listed plasma parameters include electron density $n_e$, electron temperature $T_e$, ion charge state $Z$, magnetic field $B$, plasma flow velocity $v$, Alfvén speed $v_A$, the ratio of thermal pressure to magnetic pressure $\beta$, the ratio of ram pressure to magnetic pressure $\beta_{\text{ram}}$, Reynolds number $R_e$, magnetic Reynolds number $R_m$, Peclet number $P_e$, electron mean free path $\lambda_{ei}$, Lundquist number $S$, current sheet width of the Sweet-Parker model $\delta$, and optical interferometry$^{30}$ and Thomson scattering$^{14}$. More details can also be seen from the Methods and Supplementary Fig. 2. The differences in the equation of state (EOS)$^{38}$ and opacity$^{39}$ of the Cu and CH lead to the asymmetric plasma states on both sides. For both plasmas, the thermal pressure to magnetic pressure ratio $\beta > 1$ and the ram pressure to magnetic pressure ratio $\beta_{\text{ram}} > 1$ indicate that reconnection is strongly driven$^{21,22}$.

For the following plasma colliding and reconnection process, due to low densities and high temperatures of plasmas at their interaction region, the electron mean free path $\lambda_{ei}$ comparable to the plasma scale $L$, therefore, the kinetic effects start to play key roles and kinetic PIC simulations are required$^{40-42}$. In order to connect the PIC simulation with the RMHD simulation in a self-consistent manner, a self-similar transformation is proposed and applied here, see more details in Methods. Just like the self-similarity principle of the magnetohydrodynamic equations$^{43-45}$, we choose a set of free parameters to spatially scale down the plasma parameters obtained from the above RMHD simulation to the relative small scale that is practical for kinetic PIC simulation, where the plasma properties including $\beta$, $\beta_{\text{ram}}$, the Mach number and the Alfvénic Mach number, etc., are all kept conserved between RMHD and PIC. In order to correctly evaluate the relative strength of Coulomb collisions$^{46}$, we ensure that $L/\lambda_{ei}$ remains unchanged in the two systems. Through this methodology, we carry out the whole simulation in a self-consistent manner.

After the Cu and CH plasmas collide, the supersonic inflow makes the plasma and magnetic fields pile up around the reconnection region, and the properties of the plasmas (electron density $n_e$, temperature $T_e$) and fields become almost uniform in the $z$-direction, see Supplementary Fig. 3. These make the magnetic reconnection quasi-2D, and this reconnection process can be approximated with kinetic 2D3V PIC simulations. In addition, it has also been identified that the 3D tilted geometric effect has little effect on the reconnection rate in such a strongly-driven regime$^{22}$.

The fully-kinetic PIC simulations are performed in two-dimensional (2D) $xy$ plane with the code “EPOCH”$^{47}$. Topologies of magnetic field evolutions at various times in the simulations are shown in Fig. 4a–d from $t = 1.0$ to 1.8 ns (following the previous RMHD simulation). Based on these field topologies, we also carry out the simulation for the synthetic proton radiography process, see Methods. The synthetic proton radiography images corresponding to 4a–d are shown respectively in Fig. 4e–h. We see that the Cu and CH plasma bubbles start to contact with each other at $t = 1.0$ ns [Fig. 4a], in consistence with the experimental result [see Fig. 3b]. The corresponding synthetic radiography image in Fig. 4e also show similar feature as that in the above 3b, where the slight difference may be due to lack of a driving source. At $t = 1.2$ ns [Fig. 4b], similar as the experimental results, we see that the magnetic fields are compressed and amplified in the colliding region, forming a long and narrow current sheet. Due to the plasma pressure asymmetry, we also see the current sheet drifts slowly towards the Cu plasma side.

Subsequently at time $t = 1.5$ ns, we see clearly from Fig. 4(c) that the current sheet breaks and multiple plasmoids form due to the tearing instability$^{27-29}$, and magnetic field energy dissipates at several local points (X-points), marked by the red crosses. Furthermore, we see all the plasmoids protrude into the CH plasma side and are more pronounced in the CH plasma side, which further verifying that the asymmetry of the tearing instability and magnetic reconnection. This feature is quite similar to the astronomical observations of the reconnection.

expansion velocities and magnetic fields are comparable to the experimental results shown in the Fig. 2 above, and the electron density and temperature are also close to those measured by optical interferometry$^{30}$ and Thomson scattering$^{14}$. More details can also be seen from the Methods and Supplementary Fig. 2. The differences in the equation of state (EOS)$^{38}$ and opacity$^{39}$ of the Cu and CH lead to the asymmetric plasma states on both sides.
between solar filaments and coronal loops. Again, both the X-points and plasmoids can be accurately reflected by the synthetic proton radiography, as shown in Fig. 4g, where several high-dose fine filaments appear (marked by the red-dashed circles), agreeing well with the experimental results in Fig. 3c, d, although the spatial averaging effect reduces the clarity of the experimental images. Note that the length and width of the low-dose ribbon in 4g is about $\Delta x_{\text{sim}} \sim 1.7$ mm and $\Delta y_{\text{sim}} \sim 0.25$ mm, which are also both consistent with the experimental results. At much later time $t = 1.8$ ns [Fig. 4d], we see that the magnetic fields, current sheet and plasmoids are further continuously compressed, and the distance between these plasmoids gradually increases due to stretch and ejection\(^{30,31}\) ($v \sim 10^4$ m·s\(^{-1}\)). These plasmoids and X-points (high-dose filaments) become more prominent in radiographic images, see Figs. 4h and also 3d. The number of plasmoids and X-points does not change with time, implying that the merging of magnetic islands and secondary tearing instability\(^{25-29}\) both do not occur here. The phenomenological consistency between the simulation and the experimental results verify that the tearing instability and plasmoid-dominated magnetic reconnection indeed take place in our experiment.

To reveal the inherent mechanism of the hybrid collisional-collisionless magnetic reconnection, the main parameters of both Cu and CH plasmas inside the reconnection layer obtained from PIC simulations are summarized in Table 1b, which are exactly the plasma states for magnetic reconnection. We see that since both Cu and CH plasmas are highly compressed, their densities and temperatures significantly increase, and the magnetic field strengths are amplified to more than 2 times than their initial values, see also Supplementary Note 3 and Fig. 4. The average width of the reconnection layer (current sheet) is about $2\delta_{\text{sim}} \sim 100$ μm, which is similar with the reconnected experimental result $2\delta_{\text{exp}} \sim 150$ μm. The Lundquist number $S \equiv L v / \eta$ >> 1 in both plasmas, especially in the CH plasma where $S \sim 0.5 \times 10^4$, verifying that the tearing instability can easily occur and develop. But they are still well below the threshold ($S \sim 10^7$) at which the current sheet thinning becomes significant\(^{18,49}\), i.e. the current sheet remains in the relatively static Sweet-Parker regime. The half width of the Sweet-Parker current sheet $\delta_{\text{sp}} \equiv L / \sqrt{S}$ of Cu (about 0.4$d_i$) and CH (about 0.3$d_i$) plasmas are both smaller than the ion skin depth $d_i$ or ion cyclotron radius $\rho_i$ which means the two-fluid effect\(^{22,26}\) needs to be considered. More importantly, we see that, due to the very different ion charge states $Z$ of Cu ($Z \approx 20$) and CH ($Z \approx 3.5$), the plasma on the Cu side is in a strongly-collisional state ($\lambda_{ei} \sim 100$ μm and $\lambda_{ci} / 2\delta_{\text{exp}} \sim 0.67$), while the plasma on the CH side is collisionless ($\lambda_{ei} \sim 500$ μm and $\lambda_{ci} / 2\delta_{\text{exp}} \sim 3.33$). Comparing $\delta_{\text{sp}}$ and $\lambda_{ei}$ in Cu and CH plasmas, we can see that the plasma behaves as collisional in Cu and collisionless in CH.
and CH plasmas, and take into account the experimental current sheet width $2\delta_{\text{exp}} \sim 150 \mu\text{m}$, it can be considered that the asymmetry of reconnection is mainly reflected in Coulomb collisions. That is, an asymmetric magnetic reconnection in the hybrid collisional-collisionless regime can be expected.

From both the above experimental and simulation results [comparing Fig. 3c, d, or comparing 4c and d], we estimate that the characteristic growth time of the tearing instability for the hybrid reconnection is rather fast as about $\tau_{k}\sim 0.5 \text{ ns}$, at the same order of the Alfvén transit time across the current sheet $\tau_{k} \equiv \delta/v_{A}$.

Such fast tearing instability and reconnection dynamics cannot be explained by only the two-fluid effect. This can be proved from two aspects. One the one hand, as known, the maximum growth rate of the spontaneous tearing instability from the hydrodynamic perspective is about $\gamma_{\max} \sim (v_{A}/\delta)(d_{e}/d_{i})^{0.5}(\delta/\delta)^{1.550,51}$. Substituting the reconnection plasma parameter in Table 1b into it and assuming $\delta \sim 50 \mu\text{m}$, we estimate that $\gamma_{\text{Cu}} \sim (2.5 \pm 1.0) \times 10^{8} \text{s}^{-1}$ and $\gamma_{\text{CH}} \sim (1.5 \pm 0.5) \times 10^{8} \text{s}^{-1}$, which corresponds to the characteristic growth time of the tearing instability as both larger than 10 ns, too slow to explain the experimental and simulation results. On the other hand, considering only the two-fluid effect, the predicted most unstable mode is $k_{\max} \sim (1/\delta)(d_{e}/d_{i})^{0.5}(\delta/\delta)^{1.550,51}$, which means that the most confident number of X-points in reconnection is $M = Lk_{\max}/\pi \sim 2$, also smaller than 4 observed in our experiment (see Fig. 3c).

Therefore, to explain the fast and effective tearing instability observed in our experiment, we analyze the various contributions of the dissipative reconnection electric field $E_{R}$, which after normalization is defined as the reconnection rate. The two main contributions, the non-gyrotropic component of the electron pressure tensor $E_{ZP \neq} \sim -V_{P_{\parallel}}/(\epsilon_{n})$ and the resistive component $E_{\parallel} = \eta_{J_{\|}}$, are shown in Fig. 5a, b respectively at time $t = 1.4$ ns. Their contributions varying with time from $t = 1.2$ to 1.6 ns for respectively Cu and CH plasmas during reconnection are also shown in Fig. 5c. We see clearly that the non-gyrotropic electron pressure tensor always dominates [the lower half part in Fig. 5a and the blue square symbol in Fig. 5c] in the collisionless CH plasma side, while the resistive electric field dominates [the upper half part in Fig. 5b and the red triangular symbol in Fig. 5c] in the collisional Cu plasma side. And as a whole, for the hybrid reconnection, the collisionless nongyrotropic electron pressure tensor contributes (about 75%) most of the reconnection electric field, while the resistivity only contributes ~25%. In other words, it is just the collisionless non-gyrotropic electron pressure that results in the fast tearing instability and reconnection in our experiment$^{32}$. The total reconnection electric field is about $E_{z} \sim 6 \times 10^{6} \text{ V} \cdot \text{m}^{-1}$, on the order of $0.3 \pm 0.1 v_{A,\text{loc}} B_{\text{loc}}$ after normalization [marked by the green circle in Fig. 5c], i.e., a fast reconnection rate$^{40,42}$.

To further demonstrate the dynamics of the hybrid reconnection, we also carry out RMHD-PIC simulations for the cases of the purely collisionless CH-CH and purely collisional Cu-Cu magnetic reconnection, where the drive laser and other parameters are also the same. The results are shown in Supplementary Note 4 and Fig. 5. We see that in the purely collisionless reconnection case, the tearing instability grows even more quickly, resulting in the formation of more number of multiple X-points, where the normalized reconnection electric field is $E_{z} \sim 0.5 \pm 0.05 v_{A,\text{loc}} B_{\text{loc}}$ [marked by the green star in Fig. 5c], a little higher than the hybrid case. By contrast, in the purely collisional Cu-Cu reconnection case, the resistive electric field dominates, a Sprotk-Parker-like current sheet with single X-point is formed, where $E_{z} \sim 0.16 \pm 0.03 v_{A,\text{loc}} B_{\text{loc}}$ [marked by the green diamond in Fig. 5c] is much lower. These further confirm the possibility of the occurrence of a hybrid collisional-collisionless magnetic reconnection in our experiment.

Conclusions
In summary, we have carried out the well-designed experiment on an unexplored new regime of magnetic reconnection, hybrid collisional-collisionless regime, by colliding of laser-ablated high-Z Cu and low-Z CH plasmas. Using highly-resolved proton radiography, we have directly observed the topology changes for the whole process of the plasmoid-dominated magnetic reconnection. With the self-consistent RMHD-PIC simulations, we find that the experimental reconnection indeed lies in the hybrid regime and the growth rate of the tearing instability is still extremely large, resulting in rapid formation of multiple

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**Fig. 5** Contribution terms of the reconnection electric field $E_{z}$ in the hybrid magnetic reconnection. a and b are respectively the contributions from the off-diagonal (nongyrotropic) component of the electron pressure tensor $E_{ZP \neq} \sim -V_{P_{\parallel}}/(\epsilon_{n})$ and the resistivity $E_{\parallel} = \eta_{J_{\|}}$ at 1.4 ns, where, the same as the setup in experiment, the upper half part is collisional Cu plasma (where $E_{z}$ is quantified using the color map scale from purple to green colors) and the lower half part is collisionless CH plasma (where $E_{z}$ is quantified using the color map scale from black to red colors). c shows their contributions varying with time from $t = 1.2$ to 1.6 ns for respectively Cu and CH plasmas during reconnection, the error bars represent one standard deviation. The normalized reconnection electric field $E_{z}$ (normalized to local Alfvén speed $v_{A,\text{loc}}$ and magnetic field $B_{\text{loc}}$) for respectively the cases of purely collisionless CH-CH (green star), hybrid Cu-CH (green circle) and purely collisionless Cu-Cu (green diamond) reconnections are also marked in (c), where all the values are chosen at the time when the changes of their magnetic field topologies are most significant.
plasmoids, lower than the purely collisionless case but much higher than the collisional case. We show that, in this asymmetric magnetic reconnection, the reconnection electric field show much distinct feature, which is large and grows fast at the collisionless plasma side induced by the off-diagonal (non-gyrotropic) component of the electron pressure tensor, whereas smaller and more slowly at the collisional side induced by only the resistivity.

The hybrid collisional-collisionless magnetic reconnection discussed here occurs widely in astrophysics. For example, for the reconnection between the erupting collisional filaments and the collisionless coronal loops \( \beta \), are qualitatively consistent with our results. Besides, the possible reconnections occurring between the dense accretion disk and the tenuous interstellar medium may also be in such hybrid regime. Our experimental results show that the plasmoid formation is a universal feature of magnetic reconnection, even in this hybrid regime, which has been recently observed to help facilitate the slow-to-fast phase transition of reconnection in the solar atmosphere.\(^1\) We also showed that the specific magnetic reconnection mechanism depends critically on the plasma collision rates, which significantly affect the growth of the tearing instability and further the global reconnection rate, eventually determining the energy conversion efficiency from fields to plasmas, such as heating the solar corona.\(^2\) Moreover, the lower plasma \( \beta \), higher Lundquist number \( S \) and ubiquitous guiding fields in these astrophysical environments may promote the plasmoid ejection, thereby help to establish the positive feedback for global fast reconnection.\(^3\)

However, under this experimental scheme, our experimental results are still relatively preliminary. Although we have demonstrated general features of this hybrid reconnection regime, such as current sheets and plasmoids, using proton photography, a direct and detailed comparison with purely collisional and collisionless reconnection remains for future work. There have been a large number of plasma parameter measurements, but, how to quantitatively characterize the collisionality experimentally remains a problem. Further more, how to create plasmas and magnetic reconnection with greater differences in collisionality is also a technical challenge. In view of this, our proposal and research can be seen as the first attempt to answer these questions experimentally, and will attract more attention to this hybrid reconnection regime.

**Methods**

**Experimental setup.** The hybrid collisional-collisionless magnetic reconnection experiments presented in this work are carried out on ShenzGuang II upgrade (SG-II-U) laser facility at the Joint Laboratory on High Power Laser and Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. The laser facility have 8 nanosecond (ns) pulses and 1 picosecond (ps) petawatt pulse. The main target consists of two foils with the upper half part as Cu foil of density \( \rho = 8.92 \text{ g cm}^{-3} \) and the lower half part as plastic CH foil of density \( \rho = 1.02 \text{ g cm}^{-3} \). Both foil targets have thickness of 30 \( \mu \)m and width of 1.0 mm, and parallel to each other, and there is a 0.5 mm gap between the Cu and CH targets, in order to eliminate the scattering effect of protons by the solid targets.

The two foils targets are ablated with two 3λ long laser pulses (green) that have energy about 800 ± 100 J in a 1 ± 0.1 ns square temporal profile, and the distance between the two focal spots is about 1.8 mm. The corresponding laser intensities are about 800 ± 100J in a 1 ± 0.1 ns square temporal profile, and the distance between the two focal spots is about 1.8 mm. The distance between the backlighter foil \( \text{T}_0 \) and the main foils (Cu and CH) is \( h = 10 \text{ mm} \), and that between the main foils and the RCF stack is \( L = 50 \text{ mm} \), which result in the geometric magnification factor of the proton radiography system as about \( M = (h + L)/h \approx 6.0 \).

**Path-integrated field reconstruction.** The extraction of the path-integrated magnetic field \( \Psi \) from proton radiographs in this work is done by using the algorithm and program “PROBLEM”\(^4\), where a parabolic Monge-Ampère equation is solved. Note that, the formation of the proton radiographs can be understood as following. Initially, the propagation of laser-produced proton beam initially can be regarded as a uniform expansion from a point source (laser-driven target normal sheath acceleration region) into the probing plasma region. Under the paraxial approximation, \( \mu/\rho \ll 1 \), when the proton beam arrives at the probing region, it can be regarded as a two-dimensional near-planar sheet, where \( \mu \) and \( \rho \) are respectively the plasma lateral length and the distance from the proton source to the plasma, in our experiments, \( \mu = 1 \text{ mm} \) and \( \rho = h = 10 \text{ mm} \).

Afterwards, the proton beam is deflected by the Lorentz force arising from self-generated magnetic fields in plasmas, and the lateral deflection velocity can be expressed as

\[
v(x,0) = \frac{e}{m_p} z \int_0^v d[x(s)],\]

where \( e \) is the proton charge, \( m_p \) is the proton mass, \( x(s) \) and \( d[x(s)] \) are respectively the initial proton position and the lateral deflection velocity can be viewed as the gradient \( \Psi \) of the magnetic field. The trajectory of the outgoing proton beam moves approximately in a straight line at a constant velocity, and the lateral deflection velocity \( v(x,0) \) is expressed as

\[
v(x,0) = r + r_x \frac{v(x,0)}{v_y} = r,
\]

where \( v_y \) is the proton velocity, \( r_x \) is the distance from the plasma to the RCF screen, \( r_x = L = 50 \text{ mm} \) in experiments, and \( x(s) \) is the proton position on the screen.

Eventually, the deflection effect by the magnetic field makes the initially uniform proton beam redistribute on the RCF screen as

\[
\Psi(x(s),y(s)) = \frac{1}{\text{Det}(V_{yz}(x(s),y(s)))} \Psi_0.
\]

Due to the divergence-free of magnetic field \( \nabla \cdot B = 0 \), then the deflection velocity is curl-free \( \nabla \times v = 0 \). The deflection velocity can be viewed as the gradient of some potential function \( w \) with \( \nabla \phi \), and the corresponding magnetic field potential function is expressed as

\[
A = \frac{m_p c}{e} \phi,
\]

under the quasi-two-dimensional approximation, this is equivalent to the magnetic vector potential \( A_{\mu} \), and \( A_{\mu} \sim A_{\mu}/v \).

This inversion problem is well-defined, the geometric distance and proton energy are determined in the experiments, the redistributed proton flux \( \Psi \) can be obtained from the response function of RCF optical density (OD) to proton dose, and which has an almost linear relationship in the low-dose region. The inhomogeneity of the initial proton flux \( \Psi_0 \) is ignored, see also Supplementary Fig. 1.

**3D radiation-magnetohydrodynamic (RMHD) simulation.** The three-dimensional (3D) RMHD simulations in this work are carried out by using the code “FLASHT”\(^4\), which has been developed to include many high energy density physics modeling capabilities including laser energy deposition, multi-temperature \( T_x \neq T_y \neq T_{\text{el}} \), anisotropic electron thermal conductivity, and multi-group radiation transport etc. We have also further extended the code with the self-consistent magnetic field modeling capabilities including the Biermann battery. Namely, in this simulation, we added the self-consistent magnetic field component of the Biermann battery.

The initial conditions of 3D RMHD simulations are taken following those in the experiments. The size of the simulation box is \( 4 \times 6 \times 1.5 \text{ mm}^3 \) in all \( x, y, z \) directions and the solid CH/Cu foil targets with thicknesses 30 \( \mu \)m in \( z \) direction and areas of 1.0 × 2.0 \( \text{ mm}^2 \) in respectively \( x \) and \( y \) directions are placed at the position \( z = 0.2 \text{ mm} \). The ns laser pulses with energy of 800J (a multiplier is used to account for the scattering caused by parameter instabilities and match the plasma morphology in the experiments), flat-top temporal profile of duration 0.9 ns plus
Self-consistent RMHD-PIC simulation. The fully-kinetic PIC simulations in this work are performed in two-dimensional (2D) xy plane with the code “EPOCH”47. It has been identified that the 3D geometric effect has little effect on the reconnection rate in such a strongly-driven regime.22 In order to connect the PIC simulation with the RMHD simulation in a self-consistent manner, a self-similar transformation is proposed and applied. That is, before the kinetic effects become important, RMHD is used to simulate the macroscopic states of the plasmas, and then PIC is used to simulate the subsequent kinetic processes, while ensuring a self-consistent connection between them. Just like the self-similarity principle of the magnetohydrodynamics equations48-50, we choose a set of free parameters to spatially scale down the plasma parameters obtained from the above RMHD simulation to the relative small scale that is practical for kinetic PIC simulation, where the plasma properties including $\beta$, $\rho$, $p$, $E$, the Mach number and the Alfvénic Mach number, etc. are left kept conserved between RMHD and PIC. The Coulomb collisions are also well included by making $\lambda_{\alpha} \beta$ conserved.

The principle of this method comes from the self-similarity of the ideal MHD equations51-53, that is, under a set of specific parameter transformation, $\rho_{1} = \alpha \rho_{0}$, $p_{1} = \alpha^{2} p_{0}$, $v_{1} = \sqrt{\alpha} v_{0}$, $B_{1} = \sqrt{\alpha} B_{0}$, $t_{1} = \sqrt{\alpha} t_{0}$, the form of the ideal MHD equations remains unchanged. $\alpha$, $\beta$, and $\gamma$ are the free transformation parameters. The specific values of $\alpha$, $\beta$, and $\gamma$ respectively represent different physical models. In this work, $\alpha$, $\beta$, and $\gamma$ are respectively set to 0.1, 1.0, and 0.5, and then the plasma properties are preserved in the whole simulations.

The condition for the establishment of this self-similarity is that the plasma is polytropic and ideal, which means that viscosity, electric resistivity and heat conductivity are not dominant, i.e., the Reynolds number $Re \equiv \nu \rho v / \eta$, the magnetic Reynolds number $Ra \equiv \nu / \eta / (\mu_{0} B^{2} / \rho)$ and the Pelet number $Pe \equiv n e a / \nu$ are far greater than 1.0. These dimensionless numbers, before the RMHD and PIC simulations touch each other, are listed in Table 1a. Both $Re$ and $Ra$ are far greater than 1.0. Although $Pe$ is less than 1.0, considering that the plasma corridor is approximately isothermal (see Supplementary Fig. 2) and the suppression of the electron heat flow by the magnetic fields, the coronal $Pe$ will be greater than 1.0. And the coronal plasma is approximately an ideal plasma, so it is also polytropic. Therefore under limited approximations, the laser-driven expanding plasmas can be regarded as an ideal polytropic gas, where the self-similar transformation can be applied. In the context of PIC simulations, since the plasma density has the relation $\rho = \rho_{0} e^{-p x}$ and pressure $p = n T$, the transformation parameters should be chosen as $b = \sqrt{f_{0}} / \sqrt{T_{0}}$, $f_{s0}$, $f_{s1}$, where $f_{s0}$ and $f_{s1}$ are the transformation parameters of ion mass, plasma density and plasma temperature respectively. As for the transformation parameter $a$ of length, in order to correctly account for the two-fluid effect, it should be assured that $L_{ab}$ (on the order of 100 in typical laser-ablated plasmas) remains unchanged under the similar transformations, and this constraint gives $a = \sqrt{\rho_{0} T_{0}}$, which also maintains compatibility with the Ampere’s law $J \times B = \rho_{0} a / \sqrt{\rho_{0} T_{0}}$. In this way, the self-similar transformation of ideal RMHD equations is self-consistently converted into the language of PIC simulation, that is, the transformation parameters $a$, $b$, and $c$ of RMHD variables are converted into $f_{s0}$, $f_{s1}$, and $f_{t1}$ of PIC particle variables,
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