Magnetic Reconnection of Plasma Toroids with Cohelicity and Counterhelicity

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Magnetic reconnection phenomena are investigated taking into account all three vector components of the magnetic field in a laboratory experiment. Two toroidal magnetized plasmas carrying identical toroidal currents and poloidal field configurations are made to collide, thereby inducing magnetic reconnection. The direction of the toroidal field plays an important role in the merging process. It is found that plasmas of antiparallel helicity merge much faster than those of parallel helicity. It is also found that the reconnection rate is proportional to the initial relative velocity of the two plasma tori, suggesting that magnetic reconnection, in the present experiment, is a forced phenomenon.

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Magnetic-field-line reconnection plays an important role in many plasma physics phenomena in the Universe,[1] such as the evolution of solar flares,[2] development of the Earth's magnetosphere,[3] and magnetic relaxation in laboratory plasmas for nuclear fusion research.[4] To elucidate the complicated evolution of the magnetic-field lines in a simple way, magnetic reconnection, in early research in astrophysics and solar physics, was often analyzed as a two-dimensional local phenomenon. And in laboratory plasmas, such as in devices for magnetic fusion research,[4,5] it has often been investigated as a global phenomenon—monitoring the total magnetic flux, helicity, and energy of the magnetically confined plasmas. But its local features have not been seen due to the difficulty in direct measurement of the internal structure of the magnetic-field lines.

The present paper addresses two important issues: (a) how the third-dimensional vector component of the magnetic-field line affects the connection, and (b) how the global plasma characteristics influence the local features of the reconnection. Pertinent to the results of the present experiment is a recent computer simulation[6] that examined the reconnection of field lines merging with many different angles. Fully three-dimensional geometries arise in geophysical reconnection.[7]

The most commonly used description of magnetic-field-line reconnection is shown in Fig. 1(a), based on two-dimensional (2D) analyses of magnetic-field evolution as made by Sweet, Parker, and Petschek.[8] But in actual reconnection phenomena, the magnetic-field lines have significant components in all three dimensions, as observed in solar flares and in most laboratory experiments. For example, the same 2D picture of the field line shown in Fig. 1(a), describing the merging of two

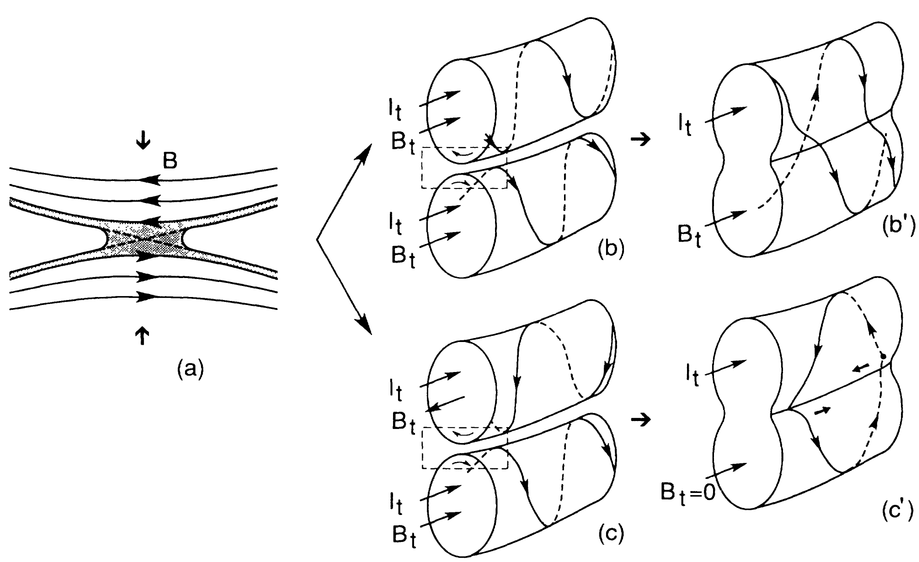

FIG. 1. Three-dimensional effects of magnetic reconnection. (a) 2D local poloidal picture of magnetic-field line at the reconnection point; (b), (b′) 3D description of evolution for merging two toroidal plasmas with equal helicity, before and after reconnection; (c), (c′) 3D description of evolution for two plasmas with opposite helicity, before and after reconnection.

plasma toroids carrying equal currents, appears quite differently in the 3D sketches shown in Figs. 1(b) and 1(c). Even though their 2D representations are identical, the three-dimensional pictures of the merging of two otherwise identical toroidal plasmas differ strongly, depending on whether their initial helicities were parallel or antiparallel. In the former case, the field lines merge at various angles, while in the latter case the field lines merge exactly with antiparallel symmetry. In addition, the internal toroidal field is necessarily accompanied by a poloidal plasma current and the additional $\mathbf{j}\times\mathbf{B}$ force changes the character of the magnetic reconnection. In general, in the case of merging counterhelicities, there is a parallel poloidal current on both sides of the reconnection region, while the current flows with an angle to each other for cohelicity merging.

There is another important difference in the reconnection patterns shown in Fig. 1(b) and Fig. 1(c). Conserving helicity, the transition from the configuration of Fig. 1(b) to Fig. 1(b′) should be globally smooth. But in the case of counterhelicity merging, Fig. 1(c) and Fig. 1(c′), the pitch of the field lines changes abruptly at the reconnection point. One expects violent plasma acceleration in the toroidal direction as the field lines contract after reconnection (a slingshot effect).

Recently, a comprehensive experiment has been proposed to investigate effects of three-dimensional magnetic-field-line reconnection on the Proto-S1 spheromak device.[9] To identify critical issues, preliminary experiments have been carried out in the TS-3 spheromak device at the University of Tokyo.[10] A related study had already been carried out on this device, investigating the global characteristics of merging spheromaks.[11] Figure 2 shows the setup for the present experiment in which two spheromak plasmas of toroidal shape are created and allowed to merge together. In the vacuum vessel there are eight sets of electrode pairs and a poloidal-field coil of 22 cm radius. The toroidal flux in each spheromak is generated by the z-discharge current between the electrodes, while the poloidal fluxes are induced by the poloidal-field coil currents. The formation of this "z-θ" pinch-type spheromak[12] is completed in 30 μsec, after which the plasma current is sustained for 70 μsec with the help of Ohmic heating induction by a central solenoid. The two spheromaks can have magnetic helicities[5] of

$$K = \pm c\psi_S\phi_S ,$$

in which ψ_S and ϕ_S are the poloidal and toroidal fluxes defined from Fig. 3 under the assumption of axisymmetry, and c is a profile factor. The polarity of K for the two spheromaks is determined independently by the direction of the z-discharge currents or of the toroidal fields. The average plasma density is about 3×10^{14} cm^{-3} (for hydrogen and helium discharges), the electron temperature $T_e \approx 5$–15 eV, the peak toroidal field $B_t \leq 1$ kG, the average beta $\langle\beta\rangle \leq 20\%$, and the toroidal

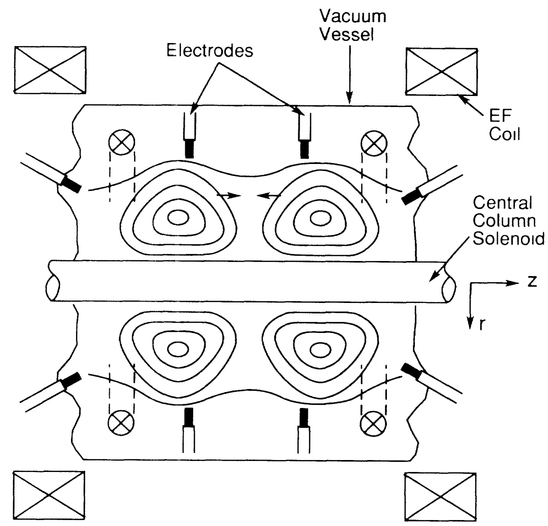

FIG. 2. Experimental setup in TS-3 device. The central column provides stability effects for spheromaks with a flux hole (currentless region) at the major axis.

plasma current $I_{pt} \approx 30$–50 kA. To investigate magnetic-field-line reconnection in the neighborhood of the midplane, $z=0$, the plasmas of major radius $R\sim15$ cm and minor radius $a\sim8$–10 cm are made to collide. Ion gyroradii are much smaller (2–5 mm) than the plasma sizes, and the magnetic Reynolds number $S=4\pi v_A a/\eta c^2 \sim 300$ based on classical resistivity. The TS-3 plasma is in the magnetohydrodynamic regime, in contrast to a previous local study of three-dimensional current sheets.[13]

To document the internal magnetic structure of the reconnection on a single shot, a two-dimensional magnetic probe array is placed on an r-z plane of the vessel. This 5×7 array (grid spacing 5 cm$\times$5 cm) is composed of 35 small pickup coils inside five glass tubes of 5 mm diam. Signals from additional monitoring probes showed this array did not disturb the plasma magnetics by large amount ($\delta B/B \leq 5\%$).

The present study focused on (i) helicity questions, that is, the effects of the third (toroidal) component of the magnetic field and (ii) the effect, on the reconnection rate, of the relative velocities of the merging plasmas.

In Fig. 3, the merging of two toroidal plasmas of the same helicity is compared with the merging of opposite helicities. The figure shows the time evolution of the poloidal flux contours derived *experimentally* from internal probe signals for the merging of cohelicities and counterhelicities. Other plasma parameters were held identical for each discharge. A merging of spheromaks of opposite helicity is shown to be more efficient compared to merging of the same helicity. In agreement with the expectation mentioned above, opposite helicities are seen to merge rapidly and sometimes violently. The merging is often accompanied by a sinusoidal oscillation of 100 kHz whose dominant toroidal mode number was measured to

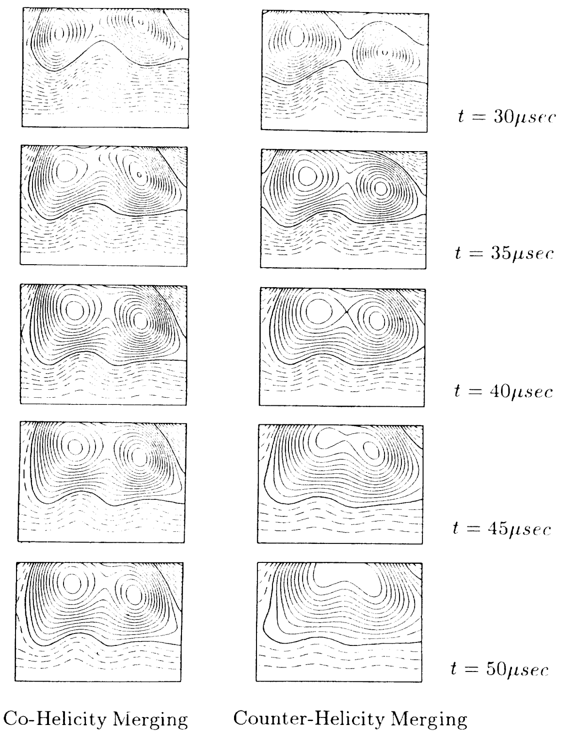

FIG. 3. Evolution of poloidal flux contours derived from magnetic probe data for cohelicity and counterhelicity merging. The plasma parameters are kept identical for the cases shown. The total plasma current $I_p = 35$–50 kA.

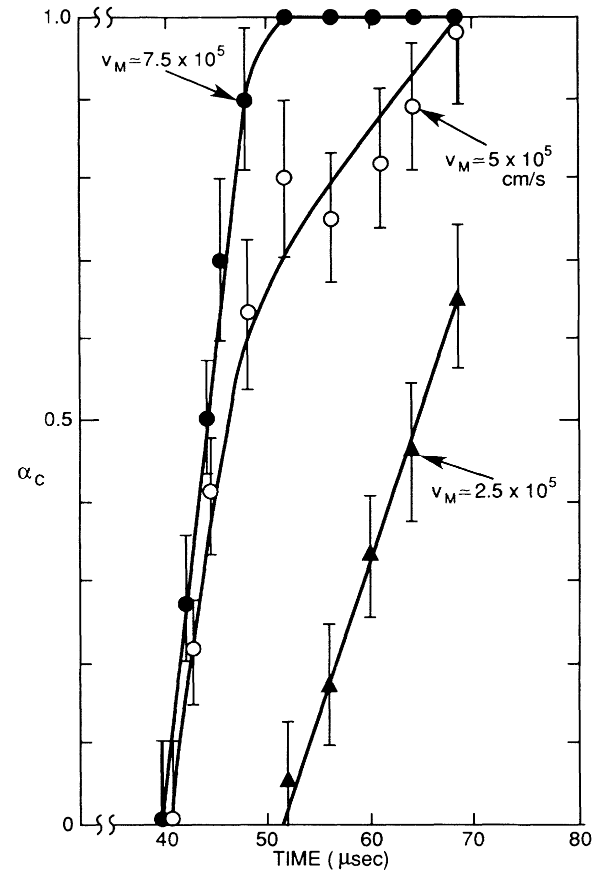

FIG. 4. Common flux ratio α_c vs time for reconnection of two counterhelicity plasmas for various values of colliding velocity, v_m.

be $n=1$ and/or $n=2$. The phase velocity of the mode is $(1\text{-}2)\times 10^7$ cm/sec, roughly equal to $v_{\text{Alfvén}}$. Merging of two spheromaks with the same helicity occurs rather smoothly and the total helicity of the spheromaks is approximately conserved, which was observed in the earlier experiment.[11]

In the case of cohelicity merging, the reconnection rate is seen to slow down significantly after $t = 40$ μsec, while for counterhelicity merging, reconnection continues until they merge completely (Fig. 3). During the initial phase, reconnection progresses with the same speed for both.

To describe the reconnection process quantitatively, we define ψ_c and ψ_p as the values of the highest common flux and peak flux of each plasma based on the solid lines of Fig. 3. We then define the common flux ratio α_c,

$$\alpha_c = \psi_c / \psi_p .$$

If the peak flux values of two plasmas do not agree (generally $\Delta\psi_p/\psi_p < 0.1$), the smaller value is used. A complete merging refers to $\alpha_c = 1.0$. Monitoring α_c versus time, one can then quantify the rate of magnetic-field reconnection by $d\alpha_c/dt$. Figure 4 depicts α_c versus time for various colliding velocities for counterhelicity merging.

It is generally observed that α_c increases initially with almost the same speed for cohelicity and counterhelicity merging, but the reconnection rate slows down significantly after α_c reaches 50% in cohelicity merging, while it progresses with approximately the same speed in counterhelicity merging until it reaches 100% as seen in Fig. 3. Here one should note that the angle of the merging field lines changes gradually from 180° to 0° for cohelicity merging as reconnection progresses, because the rotational transform of the flux hole spheromak varies radially ($q = 0$ at the edge and $q = 0.6$ at the magnetic axis,[9] where q is the inverse of the rotational transform). For counterhelicity the angle is always 180°. A recent computer simulation[6] indicates that the reconnection occurs most efficiently for a merging angle of 180° and least for 0°, consistent with the observed inefficiency of cohelicity merging in the later phases.

Another significant result of the present experiment is the observation of a strong dependence of the reconnection rate on the relative speed of approach of the two plasmas, as seen in Fig. 4. The speed, which is much smaller than $v_{\text{Alfvén}}$, can be controlled by adjusting the poloidal bias field or by the ejection speed of gun plasmas and is an important parameter in recognizing forced reconnection. In the present setup the force is estimated to be approximately proportional to the merging velocity

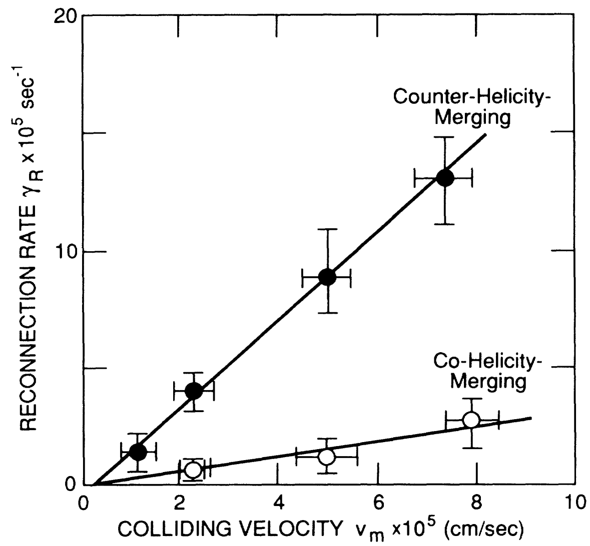

FIG. 5. Measured reconnection rate vs mutual colliding velocity v_m of two plasmas for cohelicity and counterhelicity merging.

v_m, based on our earlier spheromak formation experiments;[9,10] $v_m \sim -I_{\rm PF} \sim B_r(\text{ext})$, $F_z = I_p B_r(\text{ext})$, thus $F_z \sim v_m$ for constant plasma current I_p. Figure 5 presents the reconnection rate of two plasmas versus initial relative speed v_m for cohelicity and counterhelicity merging. The reconnection rate is defined as the time derivative of $d\alpha_c/dt = \gamma_R$ between $\alpha_c = 40\%$ and 80%. As seen in Fig. 5, γ_R increases proportionally with v_m. This trend clearly suggests the importance of an external driving force and supports an important aspect of a driven-reconnection model.[6] In recent tokamak experiments, a very fast magnetic reconnection ($\tau_{\rm rec} < 50$ μsec) has been observed during internal disruptions, and the present results might support the notion that fast plasma flow near the $q = 1$ surface induces the fast reconnection.[14]

Finally, we consider a possible cause of the observed faster reconnection for counterhelicity merging. When two plasmas of parallel toroidal fields are brought together, a new equilibrium is formed among the toroidal-field pressure (outward), poloidal-field pressure (attracting force), and the plasma pressure (outward). For the merging of plasmas of two antiparallel toroidal fields, the central toroidal field is quickly reduced to zero and the attracting force becomes so dominant that reconnection is accelerated. In addition, opposite helicity reconnection leaves a plasma far from hydromagnetic equilibrium [Fig. 1(c′)] and converts a greater fraction of magnetic energy to directed flows—an observation with implications for solar flares. Further study to determine the dependence on local[15] and global[16] structure is now needed to give a full picture of magnetic reconnection in three dimensions to address issues such as the following: (1) Do deviations from axisymmetry spontaneously arise? (2) How does directional flow energy thermalize and/or can be utilized in the fusion devices?

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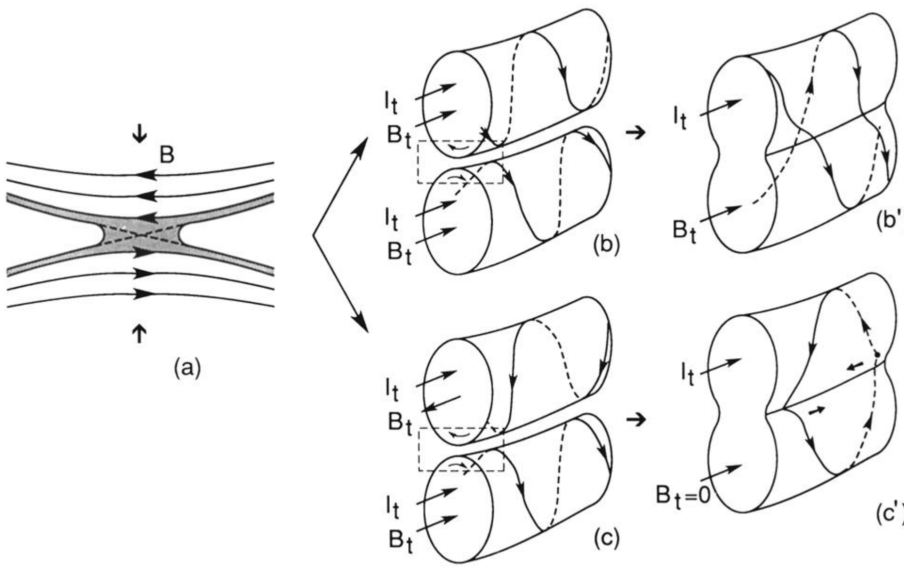

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