§11. Reversible Magnetic Reconnection

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Reversible magnetic reconnection is demonstrated for the first time by means of gyrokinetic numerical simulations of a collisionless magnetized plasma. Growth of a current-driven instability in a sheared magnetic field is accompanied by magnetic reconnection due to electron inertia effects. Following the instability growth, the collisionless reconnection is accelerated with development of a cross-shaped structure of current density, and then all field lines are reconnected. The fully reconnected state is followed by the secondary reconnection resulting in a weakly turbulent state. A time-reversed simulation starting from the turbulent state manifests that the collisionless reconnection process proceeds inversely leading to the initial state. During the reversed reconnection, the kinetic energy is reconverted into the original magnetic field energy. In order to understand the stability of reversed process, an external perturbation is added to the fully reconnected state, and it is found that the accelerated reconnection is reversible when the deviation of the E×B streamlines due to the perturbation is comparable with or smaller than a current layer width [1)].

Magnetic reconnection is considered to be a key mechanism causing conversion of magnetic energy into kinetic energy in laboratory and space plasmas. In magnetic fusion and solar corona, plasmas are subjected to an ambient magnetic field (so-called guide field), and are strongly magnetized. Studying the property of collisionless magnetic reconnection may help to understand a detailed mechanism of the sawtooth crash in the toroidal magnetic fusion experiments, where the $q = 1$ surface (q means the safety factor) is often recovered after the crash. The study may also be helpful for understanding magnetic perturbations which may affect zonal flows regulating turbulent transport.

In this work, time-reversible magnetic reconnection is demonstrated by means of the collisionless gyrokinetic simulations. First, we have presented the time-forwarded simulation starting from a sheared magnetic field with a small initial perturbation, where a current-driven instability grows with magnetic reconnection caused by electron inertia effects. The reconnection speed is accelerated when a cross-shaped structure of current density appears. Then, all field lines are reconnected (Top frames in Fig. 1). This process is similar to that observed in the previous numerical studies by fluid and gyrokinetic simulations . Even in the fully reconnected state, a strong E×B flow remains, and causes the secondary magnetic reconnection. Then, the system reaches a weakly turbulent state where a horizontal magnetic field normal to the initial field is dominant. In the weakly turbulent state following the fully reconnected one, we stopped the simulation, and stored the numerical data. Then, the time-reversed simulation is started from the saved data and by changing the time-step from Δt to $-\Delta t$, where the reconnection process described above is retraced. The reconnected magnetic field lines and the deformed distribution function in the velocity space return to their initial profiles in the time-reversed reconnection with reconversion of the kinetic energy to the magnetic one (Bottom frames in Fig. 1).

Stability of the time-reversed reconnection is examined by adding perturbations to the restart data used in the time-reversed simulation. The accelerated reconnection, which occurs before reaching the fully reconnected state in the time-forwarded simulation, is time-reversible with the transformation of the kinetic energy to the magnetic energy, when the perturbations are small. It is found that the deviation of an E×B flow streamlines through the reconnection region provides a measure of the threshold for the external perturbation preventing the reversible reconnection. When the deviation is comparable with or smaller than the current layer width, the accelerated reconnection with the cross-shaped current structure is reversible.

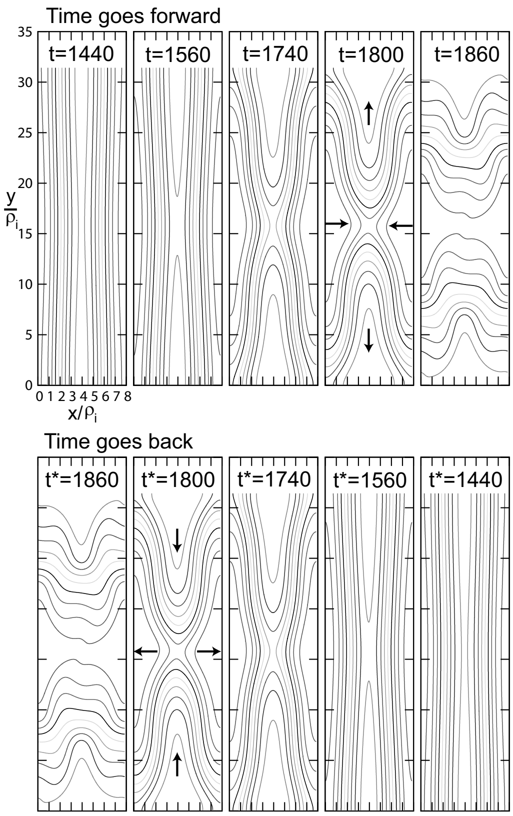

Fig. 1: Magnetic field lines projected on the reconnection plane. Time is reversed at $t = t^* = 1860$. When time goes forward (back), time is denoted by t (t^*) in the following figures. The arrows in the frames at $t = 1800$ and $t^* = 1800$ show the direction of E×B flow.

1) A. Ishizawa and T.-H. Watanabe, Phys. Plasmas **20**, 102116 (2014).