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Magnetic Field Line Analysis of Merging Formation Process of a Spherical Torus
プラズマ合体による球状トーラス生成過程の磁力線解析

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The Tokyo University Spherical Torus (TS-3 and 4) merging device experiments have demonstrated plasma merging formation of a high-beta spherical torus using two colliding plasma toroids with co-helicity and counter-helicity. The plasma merging process is analyzed by using magnetic field line tracing method. In the co-helicity merging, which forms a high-beta Spherical Tokamak (ST), the reconnecting magnetic field lines show the flux piled-up effect, and the reconnected magnetic field lines offer an overshoot to radial direction. In the counter-helicity merging, which forms a Field-Reversed Configuration (FRC), two different states are introduced. Their different characteristics are influenced by the local Hall effect.

1. Introduction

Plasma merging formation method of a high-beta spherical torus [1] has been developed in the Tokyo University Spherical Torus (TS-3/4) merging device, using two colliding plasma toroids with co-helicity and counter-helicity. In the merging process, especially ions are significantly heated, and have dramatic transition of magnetic topology through magnetic reconnection. We analyze transformation of 3-D magnetic field structure and 3-D shape of the magnetic field lines before and after magnetic reconnection.

2. Plasma Merging Experiment and Three-Dimensional Magnetic Field Line Tracing

In the TS-3 and 4 merging device, two plasma toroids are created individually by a pair of fluxcore. They attract with each other due to their parallel plasma currents, and merge on the midplane (Z = 0) through magnetic reconnection, relaxing to a high-beta spherical torus. A high-beta Spherical Tokamak (ST) is formed by merging two low-beta STs with parallel toroidal magnetic fields (co-helicity merging) as shown in Fig. 1(a). An oblate Field-Reversed Configuration (FRC) is formed by merging two spheromaks with equal but opposing toroidal magnetic fields (counter-helicity merging) as shown in Fig. 1(b). Significant ion heating is experimentally observed in counter-helicity merging, which has been explained as a result of the slingshot effect [1].

Two-dimensional (10 × 9) array of magnetic probes is located on the R-Z plane in the cylindrical

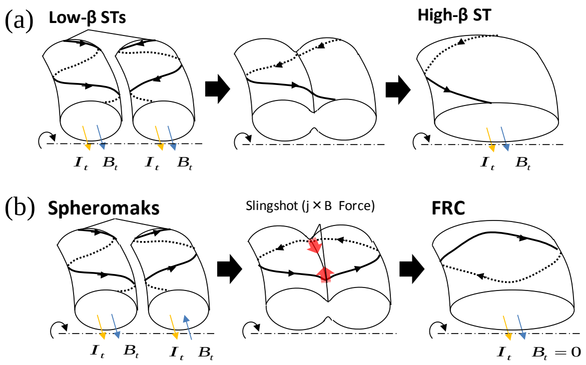

Fig. 1 Magnetic field lines of (a) co-helicity merging and (b) counter-helicity merging.

vacuum vessel of the TS-4 merging device for the purpose of measuring poloidal and toroidal magnetic fields B_z and B_t. They are used to calculate magnetic fields, poloidal flux Ψ and toroidal current density j_t. Three-dimensional magnetic field lines are traced by numerical integration (Dormand-Prince method) of the calculated magnetic field vectors in a cylindrical coordinate system.

3. Analysis of the Co-Helicity Merging Formation of a ST

Fig. 2(a) shows the two-dimensional contours of poloidal flux Ψ and toroidal current density j_t during the co-helicity merging formation of a ST. A current sheet is formed at the contacting point of the two STs with parallel toroidal currents. Magnetic reconnection progresses with the current sheet dissipation, and the magnetic configuration relaxes to a high-beta ST. Fig. 2(b) shows magnetic field lines

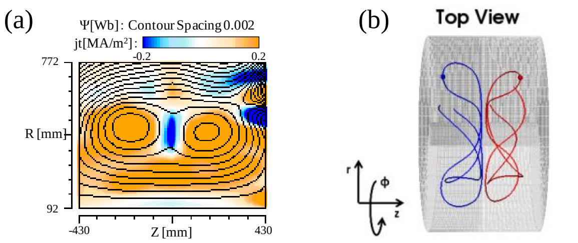

Fig. 2 (a) R-Z poloidal flux contours Ψ with toroidal current density j_t, (b) top view of magnetic field lines of two initial STs just before magnetic reconnection.

of two initial STs just before reconnection. It represents their deformation near the midplane. This fact suggests the flux piled-up effect in the current sheet [2], which contributes to fast magnetic reconnection. The reconnected magnetic field lines offer an overshoot to radial direction (not shown here), which accelerates particles.

4. Analysis of the Counter-Helicity Merging Formation of an FRC

The counter-helicity merging has two different states (Case-I and Case-O), characterized by sign of the toroidal field of the two initial spheromaks, as shown in Fig. 3 [3]. Our previous experiments indicate that an FRC formed in Case-I has better particle confinement than the other in Case-O. The reconnection (X) point of magnetic field lines is located in the outer current sheet in Case-I, while in the inner current sheet in Case-O (Fig. 4). These facts are probably explained by the tilt of reconnection planes with respect to the R-Z plane [3] or current sheet ejection [1], which make reconnection speed faster than co-helicity merging.

The reconnected magnetic field lines shows the slingshot driven by $j \times B$ force. In the vicinity of the X-point, the ion motion is detached from the electron motion, because ion gyroradius is much larger than electron one. Therefore, electrons are dominant in the current sheet, and generate the Hall effect which is experimentally identified by the sharp bending of the reconnected magnetic field lines [4]. Fig. 5 shows their magnetic field line shapes in these cases. The slingshot (red arrow) accelerates particles mainly toward inside of radial direction in Case-I, while outside in Case-O. It is also observed that the Hall effect generated by the electron motion in the current sheet (blue arrow) pulls the reconnected field lines toward toroidal direction, tilting the reconnected plane especially in Case-O.

5. Summary

We analyze the process of plasma merging formation of a ST and an FRC in detail by using three-dimensional magnetic field line tracing method. In the co-helicity merging, the flux piled-up effect is identified, which causes fast reconnection. In the counter-helicity merging, two different states of the reconnection plane and the reconnection point offer the two different slingshot motions affected by the local Hall effect, suggesting a cause and mechanism for the two different particle confinement.

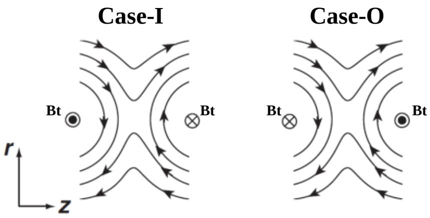

Fig. 3 Two-dimensional illustrations of reconnecting magnetic field lines in Case-I (left) and Case-O (right) of the counter-helicity merging.

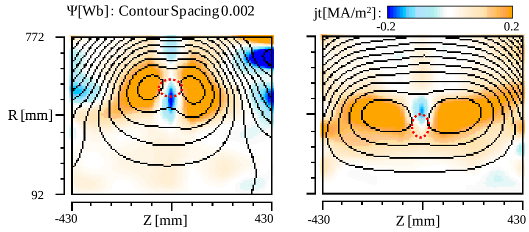

Fig. 4 R-Z poloidal flux contours Ψ with toroidal current density j_t during magnetic reconnection in Case-I (left) and Case-O (right).

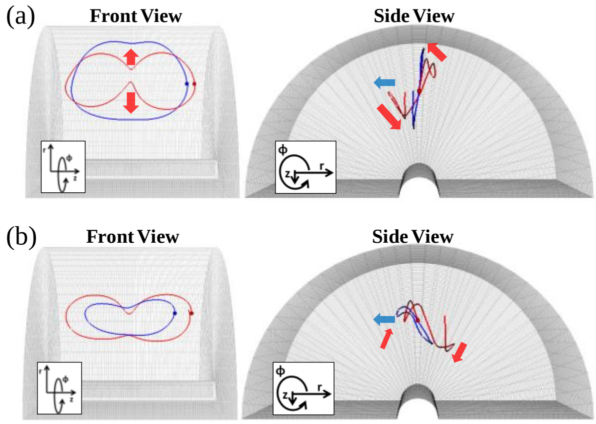

Fig. 5 Front (left) and Side (right) views of reconnected magnetic field lines in (a) Case-I and (b) Case-O during couter-helicity merging.

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