論文の内容の要旨
Thesis Summary

論文題目　Experimental Study of Dynamic Magnetic Reconnection in Tokamak Plasma Merging Experiment
(トカマクプラズマ合体実験を用いた動的磁気リコネクション現象の実験的研究)

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The formation process of magnetic fine structures in the guide-field reconnection with plasmoid dynamics has been investigated in the TS-6 tokamak plasma merging experiment. The evidence of plasmoid, formation of closed flux surface, has been clearly revealed in the two stages of reconnection process, before the initiation of fast reconnection and before entering the impulsive phase, for the first time in the 30-years history of merging-type reconnection experiment. Though the optimization of pickup coils assembly into a limited space using super high-resolution 3D printer (≤ 16 μm), our new 2D magnetic probe array satisfies ion-gyro scale spatial resolution and successfully leads to the following new findings.

A new type plasmoid, two X-points, and two current sheets are formed near the midplane during the early phase of the reconnection. The current sheet between the plasmoid and its parent toroidal plasma ring is dominant. The plasmoid with parallel plasma current is completely different from the previously reported plasmoid formed in current sheet. Although the formation condition of the plasmoid remains unsolved, we found that the plasmoid does not appear in very low gas pressure discharge. The duration and the axial size of the plasmoid are weakly related to the guide field ratio.

The dynamic evolution of the plasmoid can affect the reconnection speed and common flux ratio that is the ratio of the common flux to peak flux at the magnetic axis of the tokamak plasma ring. During the plasmoid formation, the reconnection is slow due to the plasma pileup in the current sheet and the growth of the plasmoid. After the formation, the plasmoid starts to merge with the two major tokamak plasma rings simultaneously. When the plasmoid fully merges, the reconnection speed increases rapidly and significantly, which is considered to trigger the fast magnetic reconnection (initial fast reconnection).

The plasmoid plays a key role on the ion heating around the X-points. The ions in the outflow area of both X-points are obviously heated. When the plasmoid is completely absorbed to the tokamak plasma rings, the downstream ion heating increases significantly. Right after the plasmoid absorption, the common flux ratio α reaches about 20% and the downstream ion T_i reaches about 10 ~ 12 eV, while the maximum of T_i is about 30 eV after merging (α = 100%). It suggests that a considerable amount of magnetic energy stored around the current sheets during the plasmoid formation is converted to thermal and kinetic energy of ions, providing the initial ion heating for the spherical tokamak plasma.

The initial fast reconnection lasts a few microseconds, during which the magnetic reconnection is so fast that the speed of newly reconnected flux (common flux) far exceeds that of the outflow, resulting in the rapid accumulation of common flux around the X-point. And at the same time, the common flux together with the current sheet is strongly compressed into an elongated shape by the two approaching tokamaks, so the X-point shifts outward. As the magnetic reconnection continues, the common flux is almost compressed into antiparallel lines, resulting in the decreasing of the pressure gradient in R direction inside the current sheet. Therefore, the common flux continues to accumulate and the X-point continues to shift outward, forming a transition phase of the magnetic reconnection. During this phase, the antiparallel lines of the common flux have a chance to contact each other, forming a new X-point and another plasmoid inside the current sheet. When the current sheet is compressed to a limit, it will be torn and ejected, maybe accompanied by the plasmoid ejection. The ejection of the current sheet and plasmoid can trigger the reconnection to an impulsive phase and heat the downstream ion significantly.

Although the two types of plasmoid can increase the reconnection speed and heat downstream ion significantly, their formation regimes are completely different. The first plasmoid (appears early) with parallel plasma current is formed from a part of the peripheral plasma of the tokamak plasma ring, while the two tokamak plasma rings are still in their respective formation region. Regardless of the discharge gas species, discharge gas pressure, and guide field ratio, it is always observed. Only when the discharge gas pressure is extremely low, it does not appear. It suggests that the first plasmoid has a high reproducibility and can be used as a usual phase to promote reconnection speed.

The second plasmoid is formed in the current sheet and has antiparallel plasma current. It is observed only when the current sheet is rapidly compressed to elongated shape in the high-guide field reconnection experiments, but it does not appear very often. Since its small scale, high-resolution magnetic probe array is required. However, it is difficult to achieve high resolution in both R and Z directions because of the need to ensure a plasma-passing rate in the experiments. Although the current experimental results indicate that the second plasmoid has a poor reproducibility, it may just be that we have not observed it.

Although the plasmoid is the local phenomenon at around the X-point and needs to be studied in more detail, it was confirmed that the both types of the plasmoids trigger the fast reconnection and heat downstream ion effectively.