論 文 の 内 容 の 要 旨

論文題目 Elucidation of Energy Conversion Mechanism for Electrons in Magnetic Reconnection with a Guide-Field
（ガイド磁場リコネクションにおける電子へのエネルギー変換機構の解明）

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1. Introduction

The concept of magnetic reconnection was first suggested as a mechanism for particle acceleration in solar flares. Since then, magnetic reconnection has been recognized as one of the fundamental processes in magnetized plasmas, whether in the laboratory, the solar system, or distant objects in the universe. It is widely believed that reconnection plays a key role not only in dynamic phenomena in the solar system such as solar flares, and magnetospheric substorms. It also observed as the self-organization process in fusion plasmas, typically disruptions of tokamak discharge.

Fundamentally, magnetic reconnection is the breaking and topological rearrangement of magnetic field lines in plasma during which the fast conversion from magnetic energy to particle energy occurs through acceleration and/or heating. When highly conductive plasmas carrying anti-parallel magnetic field lines are brought together, a sheet-like field discontinuity, which correspond to singularities of the current density would be caused, called “current sheet”. In the framework of ideal magnetohydrodynamics (MHD), magnetic field lines are frozen-in to the plasma and remain intact. However, when a pair of field lines approach each other, non-ideal effects become locally important. Then, a dissipation of current sheet allows the plasma diffusion and magnetic reconnection to occur.

It has been studied that the magnetic field lines, which reconnect, are oppositely directed (anti-parallel). However, it does not need to be anti-parallel in general. The component of magnetic field, which is perpendicular to the reconnection plane, is called as guide-field. The dimensionless parameter can be installed for the discussion of the guide-field effects on the reconnection. Even a small guide-field changes significantly dynamics of resonant electrons resulting in modification of the current sheet stability criteria. Particle dynamics changes from quasi-adiabatic to stochastic causing substantial asymmetry in the current structure and particle drifts. The large reconnection electric field along the magnetic field lines provides acceleration of electrons to super-thermal energy. This energetic electron in the guide-field reconnection has been observed in the solar flares, laboratory experiments and numerical simulations.

There is as of yet no consensus on how particles gain energy in the collision-less guide- field reconnection. To fill this gap, in this dissertation, energy conversion mechanisms for electrons during collision-less magnetic reconnection with a guide-field are discussed, based on measurements in the University of Tokyo Spherical Tokamak (UTST) and Magnetic Reconnection Experiment (MRX). Furthermore, the detail physics, which is difficult to address in the laboratory experiments due to the small scale of electron dynamics, is discussed based on 2D PIC simulation results by means of Plasma Simulation for Magnetic reconnection in an Open system (PASMO) code.

2. UTST Laboratory Experiments

UTST device was constructed to show the feasibility of the double null merging (DNM) method for a high β ST startup. First, the combination of the toroidal and equilibrium field generates spiral magnetic field. Then, two washer guns located inside (one is in upper side and the other one is in bottom side) are discharged to perform the pre-ionization along with the spiral field. After the pre-ionization, two initial spherical torus (ST) plasmas are produced separately in both upper and lower regions of the UTST device by ramping the PF coil current down. Two ST plasmas produced in the UTST device have the poloidal magnetic field B_p as the reconnecting field component and the toroidal magnetic field B_t as the guide-field. Merging of two ST plasmas produced the re- connection toroidal electric field E_t around the X-point.

We found that electron heating at the X-point took place during high guide-field magnetic reconnection whereas the electron temperature outside current sheet reveals clearly lower temperature than that at the X-point. Using slide-type 2D Thomson scattering measurement system, we observed that localized electron heating at the X-point forms a round- shaped high electron temperature area in sharp contrast with highly elongated current sheet. By assuming the toroidal symmetry and integrating a volume in the plasma near the X-point, the increment in electron thermal energy is obtained for 2.2 J, which is about 15% of the dissipated magnetic energy of 14 J. This conversion ratio in high guide-field ratio ~ 15 is higher than that in previous guide-field (ratio ~ 15) reconnection experiment in the TS-3 device. This can be explained by that the electron heating is caused by the parallel electron acceleration by reconnection electric field along the magnetic field line (mainly in toroidal direction) and thermalized during the guide-field reconnection.

3. MRX Laboratory Experiments

MRX device is a mid-size laboratory device specifically designed for detailed studies of magnetic reconnection. When plasma is ignited, there is global pressure imbalance because both the magnetic and plasma pressures are high near the flux cores. This pressure imbalance drives plasma inflow from the flux cores to the middle: “pushing” the magnetic flux toward the middle. This push reconnection phase begins right after the plasma formation. After the global pressure imbalance is relieved, the magnetic flux is pulled toward the flux cores from the middle and a current sheet becomes an elongated shape. This stage of the MRX discharge is called the pull reconnection phase. In the pull reconnection, the reconnection rate is relatively constant, that is called the quasi-steady state.

In this work, we used 2D magnetic probes, four Langmuir probes and a 22-tip floating potential probe. More than 1000 discharges are analyzed based on the reproducibility of the data from the 2-D magnetic probe array and a reference Langmuir probe in order to select the final data set. The main criteria are the location of the X-point and the density and temperature measured by the reference Langmuir probes at the upstream.

Electrons are significantly heated during collision-less reconnection in MRX guide-field reconnection. The electron temperature is highest near the X-point. This feature is consistent with other experiment results in TS-3, UTST and MAST. However, there is a difference between this profile and that of the other devices, that the shape of high electron temperature is elongated along with high-current separatrix. The Ohmic dissipation based on the Spitzer resistivity cannot be the main reason for the electron energy gain. The total energy of Ohmic dissipation based on the parallel Spitzer resistivity is a order smaller than the electron energy gain from the electric field. This estimation shows that the collisional drag term cannot balance the total energy gain unless the so-called anomalous resistivity exists around the X-point that is consistent with the UTST results.

In order to study the effects of the guide-field on the energy conversion mechanism, we run the experiment in MRX with varifying the guide-field ratio. It is found that the electron temperature profile depends on the guide-field ratio. It is important to note that when the magnetic energy dissipation rate, is decomposed into perpendicular and parallel components with respect to the local magnetic field lines, the parallel component is measured to be significantly larger than the perpendicular component unlike the anti-parallel reconnection experiment. These results indicate the parallel acceleration is most likely the key physics for the energy conversion mechanism in the guide-field reconnection.

4.Particle-in-Cell Simulation using PASMO code

Particle-In-Cell (PIC) method is a very intuitive method of plasma simulation where the basic scheme is to move the electrons and ions within a discrete spatial grid upon which are calculated electromagnetic fields that are self-consistent with the particle motion. Magnetic reconnection in most laboratory experiments and space phenomena occurs in open systems, where electric and magnetic fields freely expand from the downstream region and plasmas never re-enter the diffusion region after they pass through the reconnection region. Plasma encounters energy conversion event only once in the open system, while the plasma gains energy through reconnection many times in the periodic system. In this sense, we used the open boundary condition to clarify the effects of energy conversion. Furthermore, under the open boundary condition, our simulation can obtain a quasi-steady state, when the initial Harris-type sheet is exhausted and the reconnection electric field is spatially uniform and temporally constant. We can eliminate influences caused by the initial Harris- type equilibrium, where the isotropic plasma pressure balances with the upstream asymptotic magnetic pressure.

During the quasi-steady state, the parallel electric field is generated in the low-density separatrix and that accelerates electrons along the separatix, as a result, electrons from a beam component of the distribution function. When the accelerated electrons escape from the X-point and meet the cold bulk component, the thermal energy can be pile-up in there. It is also shown that electron perpendicular heating is mainly due to the breaking of magnetic moment conservation in separatrix region because the charge separation generates intense variation of electric field within the several electron Larmor radii. Meanwhile, electron perpendicular acceleration takes place manly due to the polarization drift as well as the curvature drift in the downstream near the X-point. The enhanced electric field due to the charge separation results in a significant effect of the polarization drift term on the dissipation of magnetic energy within the ion inertia length in the downstream.

5. Conclusions and Summary

The 2D electron temperature profile obtained using Thomson scattering measurement system and triple Langmuir probes in UTST and MRX respectively shows that electrons are heated around the X-point. Measurements and analyses suggest that electrons are heated by anomalous resistivity, but the precise mechanisms that generate the anomalous resistivity remain unknown. The classical Ohmic dissipation based on the perpendicular Spitzer resistivity cannot explain the measured 2D temperature profile. The required heating power exceeds that of classical Ohmic dissipation by a factor due to the high electron temperature. To explain the high electron temperature, the Ohmic dissipation must be larger than the classical value, indicating the presence of anomalous resistivity. Magnetic and electrostatic fluctuations in the lower hybrid frequency range are observed near the X-point. These fluctuations may contribute to the observed non-classical electron heating, but additional measurements on the wave characteristics are required to draw definitive conclusions.

The 1D electron temperature profile with three different guide-field ratios 1-3 in MRX suggests that the guide-field ratio plays a key role on the electron heating near the X-point. The parallel component of the magnetic energy dissipation is dominant in all three different guide-field ratios 1-3. Since this trend is also observed in 2D PASMO simulations qualitatively, the parallel acceleration is a strong candidate for the electron energization in the vicinity of the X-point.

The electron perpendicular heating mainly due to the breaking of magnetic moment conservation in the high-density separatrix is observed in 2D PASMO simulation. The charge separation generates intense variation of electric field, which is sustained by the non-ideal effects within the several electron Larmor radii. Meanwhile, electron perpendicular acceleration takes place manly due to the polarization drift term as well as the curvature drift term of the magnetic energy dissipation in the downstream near the X- point. This energy conversion mechanism can explain the elongated profile of the high electron temperature measured in MRX.