PL-22 AAPPS-DPP2020

4th Asia-Pacific Conference on Plasma Physics, 26-31Oct, 2020, Remote e-conference

Highlights of magnetic reconnection physics

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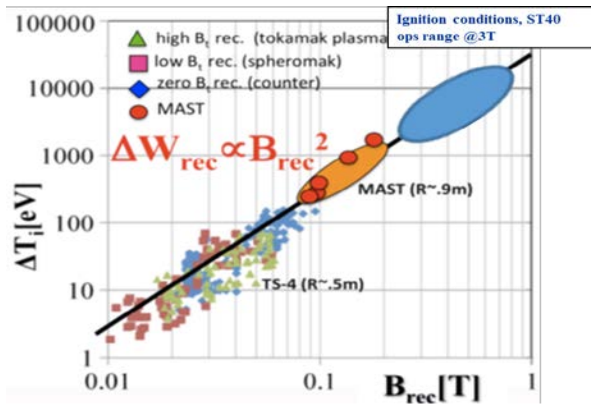
Magnetic reconnection (MR) is a crucial process in converting electromagnetic energy into plasma energy. When plasma in oppositely directed magnetic fields merge toward each other, they form current sheet around the neutral line. Because the plasma dissipation is too slow to dissipate the current sheet and avoid the plasma mass accumulation, magnetic fields reconnect to form X-line structure, which changes the magnetic field topology and allows the plasma and magnetic flux to flow away toward the downstream region.

Early concepts of MR were based on the MHD model and there are two basic MR models: Sweet-Parker model and Petschek model. The Sweet-Parker model assumes that field lines reconnect in a small dissipative diffusion region around the X-point, and plasma goes through the diffusion region and its outflow velocity is accelerated to Alfven velocity by the net electromagnetic energy in the diffusion region. The reconnection rate measured by the inflow velocity is given by $v_{in} \sim \eta^{1/2} V_A$ where η is the plasma resistivity and V_A is the Alfven velocity defined with upstream magnetic field and plasma density. The Sweet-Parker model suffers from too small reconnection rate with classical resistivity. The Petschek model bypasses the diffusion region physics by allowing reasonably fast plasma inflow velocity across the X-line separatrix into the downstream region where plasma outflow velocity is accelerated to V_A by the slow-mode shocks. The main issue of the Petschek model is that the slow mode shocks are not found in kinetic simulations, space observations and laboratory experiments.

In the last 40 years the theoretical MR physics research has evolved from MHD theory to two-fluid theory to full kinetic plasma theory. In particular, Particle-In-Cell (PIC) simulations are now common tools employed to study MR physics. Many new kinetic reconnection phenomena were discovered. For example, quadrupolar out-of-plane magnetic field due to decoupling of the electron and ion outflow velocities, plasma acceleration by parallel electric field around the separatrix regions, charge separation in the diffusion and separatrix regions which produce electrostatic potential and bipolar electric field, change of electrostatic potential structure from weak guide field case to strong guide field case. We will review the key kinetic features of the PIC simulation results. [e.g., 1, 2, 3]

The kinetic reconnection physics has also been observed in laboratory experiments and space plasma observations. Moreover, experiments have shown that the magnetic energy is mostly converted to the ions, the ion temperature gain in the downstream region is proportional to B_{rec}^2 where B_{rec} is the reconnecting magnetic field component as shown in the following figure [4, 5].



Experiments also show that the guide field does not affect much on the bulk ion heating. The B_{rec}^2 scaling of bulk ion heating has also been observed in solar wind interaction with earth magnetic field at the magnetopause [6]. This result has led to new experiments aiming to produce plasma with >10 keV ions as startup plasma for fusion. The electrons are accelerated mostly around the X-point diffusion region [7] and the accelerated electron energy can reach SXR and HXR producing energy of a few to 100 keV as observed in solar flares. In this talk we will also review these key MR features of the laboratory experiments and space observations.

The plasma system in the PIC simulations is usually too small in comparison with actual plasma systems in space and laboratory plasmas. Thus, we will also discuss the development of analytical theories that can not only provide physical understanding of the MR mechanisms, but also provide quantitative comparison with space plasma observations and laboratory experimental measurements and allow scaling to predict future experiments and space science observation missions.

References

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