CD-I9 AAPPS-DPP2020

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

Non-Maxwllian velocity distribution formed by Pick-Up-like behaviors of protons during magnetic reconnection

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Magnetic reconnection is a fundamental process of the energy rapid release and an active research topic. Plasma heating is one of the important issues in magnetic reconnection. In this work, the ion heating mechanism during magnetic reconnection in the presence of a guide magnetic field is investigated by means of particle simulations.

Our simulations have demonstrated that ring-shaped [1, 2] and arc-shaped (as shown in Fig. 1(a)) [3] velocity distributions of protons are formed in the downstream. The motion of ions forming such velocity distributions are the Pick-Up-like[4,5]. Upon entering the downstream across the separatrix, ions behave as nonadiabatic. They suddenly feel the electromagnetic field in the downstream, which is quite different from that in the upstream. Thus, they enter the downstream with a velocity much smaller than the reconnection outflow speed. They move in the outflow direction owing to ExB drift while rotating around the guide magnetic field, and form the ring-shaped or arc-shaped velocity distribution (the basic theory). This means that ions are effectively heated in the downstream, because velocity distribution is broadened compared with a Maxwellian distribution, which is satisfied in the upstream [1-3].

Recently, our simulations show various shapes of strange (non-Maxwellian) velocity distributions as shown in Figs. 1(b)-(d), where a ring with an attached arc [6], a ring with a separated arc, and a “turn U”-shape are displayed. The behaviors of ions responsible for the strange distributions are the Pick-Up-like as well. The formation mechanism of the strange velocity distributions can be explained by extending the basic theory for the ring-shaped or arc-shaped distribution to the following extended theory. In the basic theory, it has been postulated that ions enter the downstream with almost zero velocity, because they are not accelerated much upon passing the separatrix, which is the narrow boundary layer between the upstream and downstream. The extended theory, in contrast, allows a finite velocity of ions upon entering the downstream. Ions are accelerated perpendicular to the outflow direction in the separatrix and thus enter the downstream with a finite velocity perpendicular to the outflow. The gyration speed of the ions, hence, is larger than that for the basic theory. Such ions form an arc structure attached to a ring or separated from a ring. Furthermore, the basic theory has postulated another situation that the electromagnetic field is uniform in the downstream. In contrast, the extended theory allows spatial change in the electromagnetic field in the downstream. This extension of the theory leads to accounting for a “turn U”-shape structure.

Lastly, we estimate the effects of strange structures of velocity distribution on the effective heating. Among the various shapes, the separated arc significantly contributes to an enhanced increase in the ion effective temperature, because the separated arc makes velocity distribution be greatly broadening. We demonstrate that in one run of the simulations, the separated arc makes the effective temperature be nearly double.

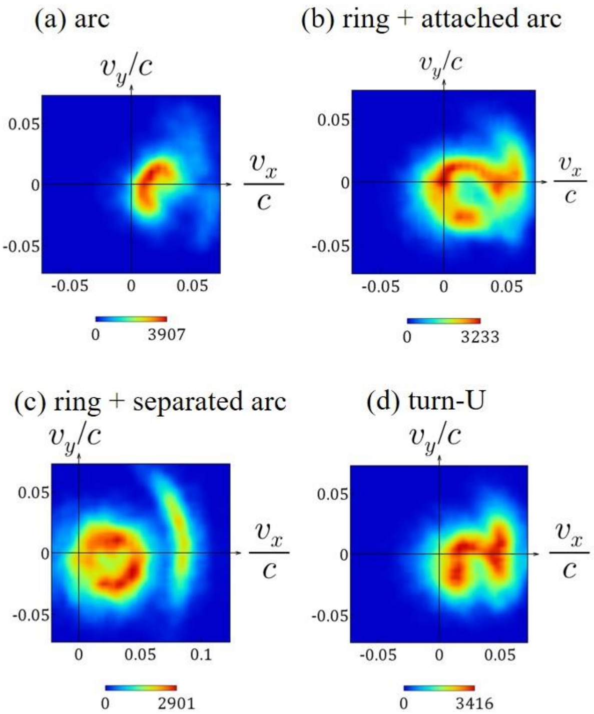

Figure 1 Various shapes of non-Maxwellian ion velocity distributions formed in magnetic reconnection.

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