Kinetic picture of the energy conversion mechanism of collisionless driven reconnection in the presence of a high guide field

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We made the first 2D PIC simulation \cite{1} for reconnection region of two merging spherical tokamak (ST) plasmas and found (1) significant ion heating in the downstream region during magnetic reconnection and (2) its fast conversion from poloidal magnetic energy into ion kinetic / thermal energy under high guide field condition.

The high-power reconnection heating has been studied in TS-3, TS-4 and MAST merging ST experiments as a promising solenoid (CS)-less start-up with significant heating. As shown in Fig.1, two ST plasmas axially merge together, forming a current sheet around the X-point. An important question is how the magnetic reconnection converts magnetic energy of two ST plasmas into thermal/ kinetic energy of the produced ST and whether the high guide field decreases the conversion rate or not. Our 2D PIC simulation including \(2 \times 10^8\) particles in a domain \(x \times y = 512 \times 256 \lambda_{De}\), where \(\lambda_{De}\) is Debye length with \(q = B_{z0}/B_{p0} = 4\), reveals fast conversion from magnetic energies to ion thermal/ kinetic energies in downstream regions.

Fig. 1 Schematic view of merging experiment and our simulation (slab) model for its reconnection area.
Figure 2(a) shows time evolutions of volume averaged $\mathbf{E} \cdot \mathbf{j}$, $\mathbf{E} \cdot \mathbf{j}_i$ and $\mathbf{E} \cdot \mathbf{j}_e$ during the PIC simulation. Since the temporal change of the total field energy is described as $d/dt \int d^3x \left( (\mathbf{B}^2 + \mathbf{E}^2)/8\pi \right) = \int d^3x \left( \nabla \cdot (\mathbf{B} \times \mathbf{E})/4\pi - \mathbf{E} \cdot \mathbf{j} \right)$, the energy conversion from the magnetic field to the plasma pressure is denoted by $\mathbf{E} \cdot \mathbf{j}$. As shown in Fig. 2(a), $\langle \mathbf{E} \cdot \mathbf{j} \rangle$ increases significantly from 20 to 40 $\omega_{ci0}^{-1}$, releasing the poloidal (reconnecting) magnetic field energy through the reconnection. The terms $\mathbf{E} \cdot \mathbf{j}_i$ and $\mathbf{E} \cdot \mathbf{j}_e$ are energy sources for ions and electrons, respectively. The energy conservation for each species is described by the following equation: $\partial W_{tot,q}/\partial t + \nabla \cdot \left( 1/2 m_q v_q^2 \mathbf{v}_q \right) = \mathbf{E} \cdot \mathbf{j}_q$, where $W_{tot,q}$ is a energy density $W_{tot,q} = \int d^3v m_q v_q^2/2 f_q$, $m_q v_q^2 \mathbf{v}_q = \int d^3v m_q v_q^2 \mathbf{v}_q f_q$, and $q$ denotes ions or electrons. Using Gauss’s theorem, the increase in $\langle \mathbf{E} \cdot \mathbf{j}_q \rangle$ (Fig. 2(a)) indicates an increment of the total energy for both species during magnetic reconnection under the quasi steady state condition, where $\partial W_{tot,q}/\partial t = 0$. Since the energy gain of electron is caused by field-aligned electric field [2], Figs. 3 (a),(b) indicate the physical picture of energy gain of ions during the single time slice between black shaded region ($t \omega_{ci0} = 36.0 \sim 39.2$), where $\langle \mathbf{E} \cdot \mathbf{j} \rangle$ is maximum. The scale length and time scale are normalized by an ion gyroradius $\rho_{i0} = v_{th,i}/\omega_{ci0}$ and ion gyrofrequency $\omega_{ci0} = eB_{z0}/m_i c$, respectively. Under the high guide field condition, field-aligned acceleration of electrons forms quadrupole structure of electrostatic potential as shown in bottom panel of Fig. 2(b). Due to strong repulsion force of the positive pairs of this electrostatic potential, the ion current becomes a sheared profile as shown in Fig. 3(a). The sheared current profile obtains energy from in-plane electromagnetic field ($\mathbf{E}_p$) through $\mathbf{E}_p \cdot \mathbf{j}_i$ as shown in Fig. 3(b), exhausting the high-energy ion outflow. Here, we ignore the energy gain from electrostatic potential because $\langle \mathbf{E}_{st} \cdot \mathbf{j}_i \rangle$ vanishes under the strong guide field. We note that the sequence of energy transfer process, especially for ions, is revealed for the first time by our 2D PIC simulation.
Fig. 3(a) ion poloidal current vector ($j_z, j_p$) and color contour of $j_z, j_p$, (b) poloidal electromagnetic electric field vector ($E_{mg,p}$) and color contour of $E_z$.

Figure 4(a) shows 2D poloidal flux contours under the high guide field ($B_t \sim 4B_{fl}$), where blue lines indicate separatrixes. Figure 4(b) shows the profiles of energy for both ions and electrons along $y \approx 10$ and along $x \approx 23$, where $W_k = 1/2 m_q n_q u_q^2$ and $u_q = \int d^3v v_q f_q$. The separatrix is located around $y \sim -5, 7$. Obviously, both of ions and electrons energies are observed to increase significantly inside the separatrix. The electron energy is mostly thermalized, because $W_{k,e}$ is much smaller than $W_{tot,e}$, and its peak position exits around separatrix ($y \sim 7$) where electrons are energized by the strong
field-aligned acceleration by $E_z$ together with the trapping effect [2]. The term $W_{tot,i}$, which is almost equal to $W_{k,i}$, is about three times larger than $W_{tot,e}$ except for the separatrix, indicating that the magnetic reconnection transforms large portion of magnetic energy to ion kinetic energy. In the tokamak merging experiment, this kinetic energy of ions is dissipated into thermal energy through fast shock or viscosity [3], resulting the high poloidal beta value of produced ST plasmas after merged. Figures 5 show 2D contours of ion temperature (kinetic energy) in one side of the downstreams for three different values of guide field. The black lines in the three figures represent the same poloidal flux line, confirming the reconnection with three different guide fields are almost in the same stage. Remarkably, the peak ion energy slightly increases with guide field in our PIC simulation. This fact agrees well with the recent MAST merging experiment.

In summary, the PIC simulation indicates the significant increase in ion energy during magnetic reconnection even if the guide field $B_z$ is as high as $4B_{\parallel}$. The reconnection outflow accelerates ions mostly by electromagnetic electric field and partly by the electrostatic electric field formed by the field-aligned acceleration of electrons. The magnetic reconnection makes efficient conversion of the poloidal magnetic energy into the ion kinetic energy, in agreement with the recent tokamak merging experiments. These results suggest that the merging/reconnection is a promising initial startup and heating method for high-beta economical ST reactors.

Fig. 4 2D profiles of ion energies with three different values of guide field: $q = \frac{B_{\parallel}}{B_{po}} = 0.25$, 1 and 4.

References