Magnetic Reconnection Physics for Low and High Guide Fields

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Magnetic reconnection is an important physical process to convert magnetic energy into plasma energy. In experiments, space observations and PIC simulations [e.g., 1-7], both ion and electron energy gains are proportional to B_p^2/n, where B_p is the reconnecting poloidal magnetic field in the *x*-*y* plane and *n* is the plasma density. The results are not sensitive to the guide magnetic field $\vec{B}_z$ strength although the particle dynamics are quite different for low ($B_z << B_p$) and high ($B_z >> B_p$) guide field cases.

For $B_z << B_p$, the merging magnetic field $\vec{B}_p$ is mainly in the *x*-direction and the merging direction is in the y-direction. With neutral sheet located at $y=0$ ions are unmagnetized in the ion orbit meandering region ($|y| \le \ell_{mi}$) where ions are accelerated by the reconnection driving $\vec{E}_z$. Similarly, electrons are unmagnetized in the electron orbit meandering region ($|y| \le \ell_{me} < \ell_{mi}$). Thus, charge separation and an electrostatic potential well Φ and large electrostatic E-field $\vec{E}_{es}$ ($>> |\vec{E}_z|$) in the *y*-direction are formed in the $|y| \le \ell_{mi}$ region. In the $\ell_{me} \le |y| \le \ell_{mi}$ region electrons are still magnetized and have a large $\vec{V}_E = c\vec{E}_{es} \times \vec{B}_p / B^2$ drift velocity in the z-direction. The $\vec{v}_z \times \vec{B}_y$ force rotates $\vec{v}_z$ toward the outflow direction. The ion outflow velocity $\vec{V}_{io}$ reaches the poloidal Alfven velocity $V_{Ap} \equiv B_p/(4\pi n_i m_i)^{1/2}$, and the electron outflow velocity reaches a super-Alfvenic velocity $V_{eo} >> V_{Ap}$. The analytic theory [5] shows that the potential well drop is $\Delta\Phi \approx (B_p^2/4\pi n_{in} e)(1+\ell_{me}/\Delta)\Lambda$ where $\Delta = B_p/4\pi n_{in} e$, $\ell_{mi}/\Delta = (m_i v_i / m_e c)\omega_{pe}^2/\omega_{ce}^2$, $\Lambda = e^{(\ell_{mi}-\ell_{me})/\Delta}\Gamma/2$, $\Gamma = n_0/n_{in} - 1 > 0$, n_0 is the averaged ion density in the $\ell_{me} \le |y| \le \ell_{mi}$ region, and n_{in} is the ion density at $|y| = \ell_{mi}$. Note that $0.2 < (1+\ell_{me}/\Delta)\Lambda < 0.5$ for most plasma parameters. Then ion energy gain from the potential drop is $U_i \approx e\Delta\Phi$. The electron energy gain in the current sheet is $U_e = (B_p^2/4\pi n_{in}) S_{evz}^2 (\ell_{me}/\Delta)\Lambda$, where S_{evz} is the average electron velocity enhancement due to E_z acceleration in the $|y| \le \ell_{me}$ region over $\vec{V}_{Ez}(y = \ell_{me})$.

For $B_z >> B_p$, both electrons and ions are magnetized in the entire reconnection region. Near the field line separatrices the parallel E-field $E_\parallel = (E_z B_z + E_p B_p)/B \neq 0$ because $|E_p B_p|$ becomes smaller and $E_z B_z$ is approximately uniformly constant. Particles are accelerated by $\vec{E}_\parallel$ to gain large parallel flow velocities with $|\vec{V}_{e\parallel}| >> |\vec{V}_{i\parallel}| \sim |\vec{V}_{i\perp}|, |\vec{V}_{e\perp}|$. The flow velocity along $\vec{B}_p$ for electrons is given by $\vec{V}_{ep} \approx V_{e\parallel}\vec{B}_p / B$ except near the X-line, and $\vec{V}_{ip} \approx (\vec{V}_{i\perp} \bullet \vec{B}_p)\vec{B}_p / B_p^2$ for ions. For $B_z > 0$ and $E_z < 0$, $E_\parallel < 0$, $V_{e\parallel} > 0$ and in the poloidal plane electrons flow mainly along $\vec{B}_p$ to accumulate density and net negative charge and produce negative Φ on the $\vec{B}_p$ pointing side. On the anti-$\vec{B}_p$ side the net charge and Φ are positive. Thus, a quadrupolar potential structure is formed around 4 separatrix arm regions. An electrostatic E-field $\vec{E}_{esp}$ is produced along $\vec{B}_p$. Because $|E_{esp}|$ on the $\Phi < 0$ side is larger than $|E_{esp}|$ on the $\Phi > 0$ side, thus $E_\parallel \approx 0$ on the $\Phi < 0$ side and $E_\parallel$ is finite on the $\Phi > 0$ side. Thus, $E_\parallel$ is finite around the $\Phi > 0$ pair of separatrix arms and $E_\parallel \approx 0$ around the $\Phi < 0$ pair of separatrix arms. A larger electric field $\vec{E}_{es,y} \approx E_y \hat{e}_y$ across the downstream region is produced, and the ion outflow velocity is given by $V_x \approx cE_y / B_z$. We obtain $\Phi^2 \sim T_i B_p^2 / 4\pi n_{in} e^2$ where T_i is the ion temperature. If Φ varies mainly across the current sheet width Δy, then $E_y \approx \left(T_i B_p^2 / 4\pi n_0 e^2\right)^{1/2} / \Delta y$, and $V_x \approx (\rho_i / \Delta y) V_{Ap}$ where ρ_i is the ion gyroradius, and the ion kinetic energy is $U_i \approx (\rho_i/\Delta y)^2 B_p^2 / 8\pi n_{in}$. If the current sheet width Δy is compressed to ρ_i, then $U_i \approx B_p^2 / 8\pi n_{in}$. The above results are consistent with the experimental results [1-4].

References

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