Gyrokinetic simulations of magnetic reconnection in non-uniform plasmas

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Abstract

A two-dimensional gyrokinetic particle-in-cell (2D-gyroPIC) model, designed to simulate driven magnetic reconnection in the VINETA-II experiment, has been employed to study the influence of plasma resistivity on the reconnection rate in non-uniform plasmas.

Introduction

The transfer of magnetic to kinetic energy during magnetic reconnection in low-collisionality systems, such as tokamaks and solar flares, proceeds orders of magnitude faster than expected from MHD theory. In order to have predictive models for the quantitative spatial and temporal evolutions of reconnection it is necessary to understand the influence of plasma parameters on the reconnection process [1, 2].

Based on a Vlasov–Ampère–Poisson gyrokinetic particle-in-cell code (gyroPIC) [3], a two-dimensional periodic slab model for studies of magnetic reconnection in low-beta plasmas [4] has been implemented to support the experimental efforts at the VINETA-II linear device [5, 6]. The experiment is designed to produce plasmas and magnetic-field configurations over a wide parameter range, thereby allowing for 3D-studies of slow collisional to fast collisionless reconnection. As illustrated in Fig. 1 the prescribed magnetic geometry consists of an azimuthal separatrix field and an axial guide field. Private flux is driven toward the magnetic X-point to initiate reconnection. The plasmas, with profiles peaking at the X-point, have densities ranging over $n = 10^{16-19}$ m^{-3}, electron temperatures $T_e = 2 - 6$ eV, and ion temperatures of $T_i \approx 0.1$ eV.

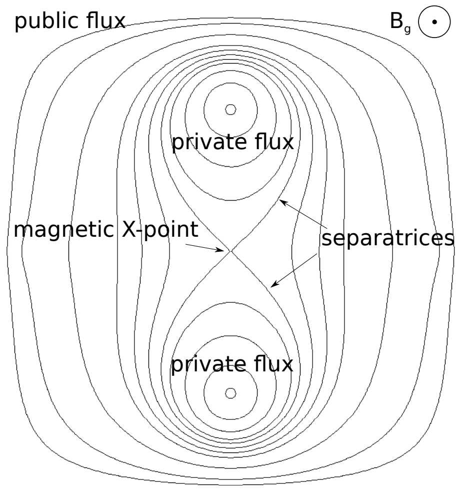

Figure 1: *The magnetic geometry of the model is illustrated with flux surfaces of constant A_z. Perpendicular to the azimuthal field is a guide field B_g.*

Reconnection Rate

The magnetic geometry of the model is described by $\mathbf{A} = A_z\hat{\mathbf{z}}$ and $\frac{\partial A_z}{\partial z} = 0$ so the induction in the system is

$$\frac{\partial A_z}{\partial t} = -\mathbf{v}_{A_z} \cdot \nabla_\perp A_z + \frac{\eta^*}{\mu_0}\nabla_\perp^2 A_z, \quad (1)$$

where η^* denotes the plasma resistivity. Magnetic flux thus propagates through the plasma at

$$\mathbf{v}_{A_z} = \frac{\left|\frac{\partial A_z}{\partial t} - \frac{\eta^*}{\mu_0}\nabla_\perp^2 A_z\right|}{|\nabla_\perp A_z|^2}\nabla_\perp A_z, \quad (2)$$

with the velocity depending linearly on the local resistivity. At the X-point, where the gradient of A_z is zero, the flux reconnects at a rate of

$$\mathscr{R} = \left|\frac{\partial A_z}{\partial t}\right| = \frac{\eta^*}{\mu_0}\left|\nabla_\perp^2 A_z\right| = |E_z|. \quad (3)$$

In a plasma it is therefore the local X-point resistivity together with the divergence of the gradient of A_z (current density) that determines $\mathscr{R}$.

Plasma Resistivity

Where the driven flux penetrates the plasma the inductive electric field E_z will follow the reconnection drive frequency $\omega = 2\pi f_D$. The resistivity parallel to the field lines can be described in terms of $\eta_{||}^* = \eta_{||}^c + \mathrm{j}\eta_{||}^i$ where the collisional resistivity $\eta_{||}^c$ accounts for electron–ion Coulomb collisions and the $\pi/2$ phase-shifted inductive resistivity $\eta_{||}^i$ is due to electron inertia. Applying Spitzer resistivity for the collisional term, the parallel Ohm's law may be written

$$\hat{E}_z \cos\omega t = \frac{\pi\zeta e^2\sqrt{m_e}\ln\Lambda}{(4\pi\varepsilon_0)^2 T_e^{3/2}}\hat{J}_e\cos\omega t + j\frac{m_e\omega}{n_e e^2}\hat{J}_e\cos\omega t = \sqrt{(\eta_{||}^c)^2 + (\eta_{||}^i)^2}\hat{J}_e\cos(\omega t + \varphi). \quad (4)$$

The resistive term $\eta_{||}^c$ is independent of density, but a strong function of electron temperature. The inductive term, on the other hand, is independent of temperature and instead scales linearly with drive frequency and inversely with electron density. Figure 2 displays the complex resistivity terms as function of density, temperature, and drive frequency. The relative importance of the collisional and inductive parts of the complex resistivity strongly depends on the plasma parameter regime.

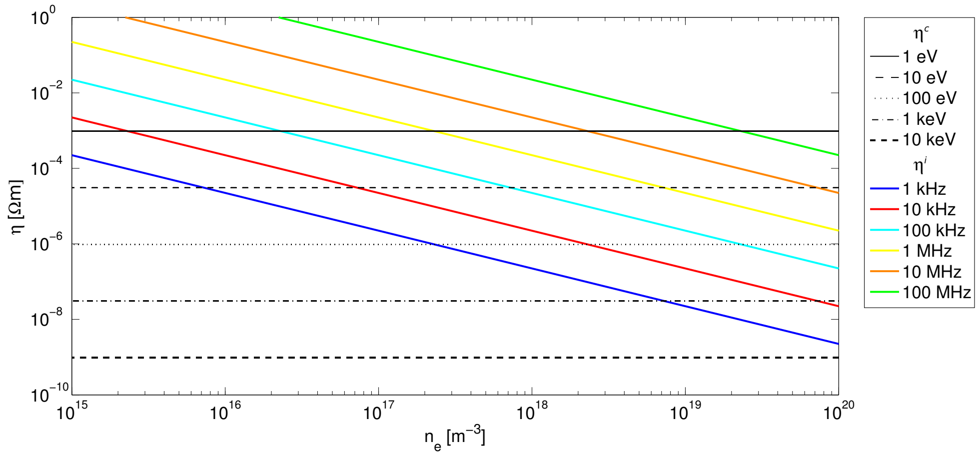

Figure 2: *Complex plasma resistivity* $\eta^* = \eta^c + j\eta^i$ *as function of* n_e*,* T_e*, and* f_D*.*

Simulations of Collisionless Reconnection

The reconnection rates $\mathscr{R}$ for plasmas with flat temperature profiles of $T_e = 4\ eV, T_i = 0.2$ eV and Gaussian density profiles with peak densities at the X-point in the 10^{14-17} m^{-3} range and widths of $\sigma = 11 - 57$ mm and have been calculated for $f_D = 50$ and 100 kHz. According to Fig. 2 the inductive resistivity for these plasmas is larger than the collisional resistivity. An example of the time evolution of A_z, E_z, J_e, and J_i at the X-point, where the inductive field is parallel to the magnetic field, is shown in Fig. 3. The quantities follow the drive frequency and, as expected, there is a phase shift of the currents relative the electric field. The current sheet is dominated by electron flow.

Calculated reconnection rates for a distribution of $\sigma = 42$ mm for the two drive frequencies are shown in the top panel of Fig. 4. $\mathscr{R}$ shows the same frequency dependence as the inductive resistivity term. The bottom panel of the same figure shows how the rate normalized to vacuum reconnection, $\mathscr{R}' = \mathscr{R}/\mathscr{R}_0$, varies with distribution widths for $f_D = 100$ kHz. At high densities, where the skin depth $\delta_e = \frac{c}{\omega_{pe}}$ gets small, the flux is prohibited to fully penetrate to the X-point due to the generation of currents at the plasma edge. Current sheets for four plasmas subject to the same drive of $f_D = 50$ kHz are displayed in Fig. 5.

Summary and Discussion

In ideal plasmas the time scale of the fluctuation initiating reconnection determines the resistivity together with the plasma density. The influence of these parameters on the resulting reconnection rates for high-guide-field non-uniform plasmas are investigated using a gyrokinetic slab model tailored to the experimental conditions of the VINETA-II device. A full 3D model with logical sheath boundaries, where also non-uniformites along the magnetic field can be included, is currently being developed [4].

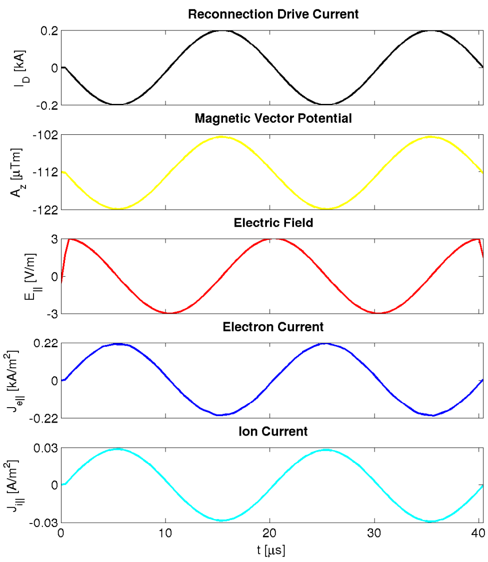

Figure 3: A_z, E_z, J_e, and J_i at the X-point as function of drive current for a plasma with $n = 7.8\times10^{14}\ m^{-3}$ and $\sigma = 27$ mm.

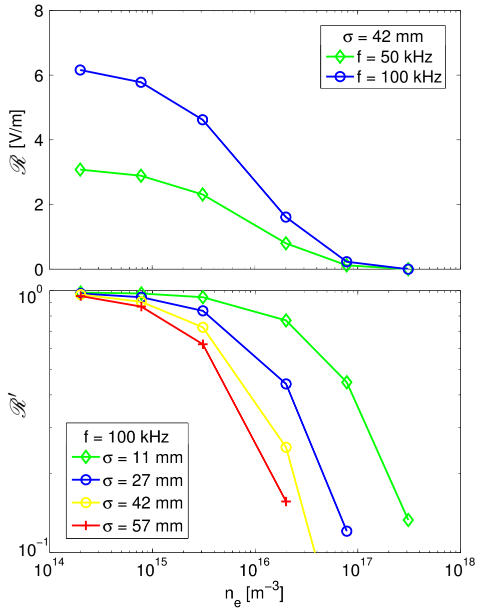

Figure 4: **Top:** *$\mathscr{R}$ as function of f_D and n_e*
Bottom: *$\mathscr{R}'$ as function of σ and n_e*

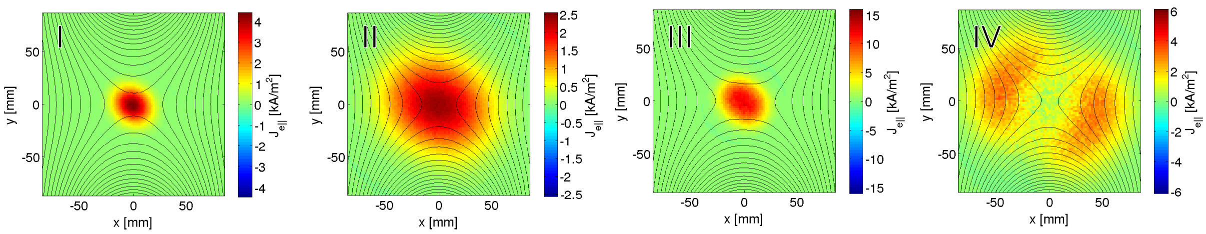

Figure 5: *Generated electron current sheets for $f_D = 50$ kHz.* **I** *$n = 2.0\times10^{16}\ m^{-3}$, $\sigma = 11$ mm* **II** *$n = 2.0\times10^{16}\ m^{-3}$, $\sigma = 27$ mm* **III** *$n = 3.1\times10^{17}\ m^{-3}$, $\sigma = 11$ mm* **IV** *$n = 3.1\times10^{17}\ m^{-3}$, $\sigma = 27$ mm*

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