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Cross-field diffusion of magnetized low temperature plasmas near separatrix: A Particle-In-Cell simulation study

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The study of diffusion in magnetized low temperature plasmas (LTP) offers a critical framework for understanding fundamental cross-field transport phenomena. Characterizing transport near the separatrix is essential for enhancing plasma confinement in fusion devices, interpreting transport mechanisms in astrophysical environments, and improving various plasma-based applications. This work investigates LTPs confined in the magnetic field configuration containing X-point using 2D electrostatic Particle-In-Cell (ES-PIC) simulations.

One of the analytical magnetic configurations that contain magnetic X-points is the two-wire model (TWM) [1]. The TWM describes the magnetic field formed by a pair of parallel wires (located at $y = \pm\ell$) with currents flowing in the same direction (Figure 1a). The magnetic field vectors circulate counterclockwise around each wire, and the magnetic field strength approaches zero at the origin (X-point). The magnetic field lines follow the analytical geometry of Cassini ovals [2]. Cassini ovals are curves consisting of points for which the products of distances to the two foci are constant, i.e. $r_+ r_- = \mathrm{const} = \ell^2 s^2$. $\zeta = \ln s^2$ is defined as the field line value (FLV), and the separatrix corresponds to $\zeta = 0$ (Figure 1b).

2D ES-PIC simulations of LTPs confined in the TWM are performed using EDIPIC-2D [3]. EDIPIC-2D is an open-source simulation code designed for modeling LTPs. This code supports conducting and dielectric boundaries and internal objects, and it allows for constant injection of particles. Additional external magnetic fields can be applied to the system, and Monte Carlo collision (MCC) algorithms are implemented.

The aim of this numerical investigation is to analyze plasma confinement and transport across the field lines of the TWM. To simulate the plasma diffusion starting from the cores, primary electrons with tens of eV are emitted from the wires. The system is initially empty, and ionization of background neutral helium produces electron and ion pairs to fill the system with LTP.

The simulation results reveal notable features near the X-point and the separatrix, including the formation of a nearly flat density region (Figure 1c). The flat electron density profile around the separatrix indicates that the X-point acts as a weak transport barrier allowing rapid cross-field diffusion and equalizing densities on either side. To investigate how fundamental plasma parameters affect the separatrix cross-field transport barrier, plasma density, magnetic field strength, and neutral pressure (collision frequency) are independently varied for different cases of simulations. The sensitivity of near-separatrix transport to each control parameter is qualitatively evaluated. In addition, the simulation results are compared with the experimental observations from the magnetic X-point simulator system [4], providing a basis for validating the numerical model and identifying key physical mechanisms.

References
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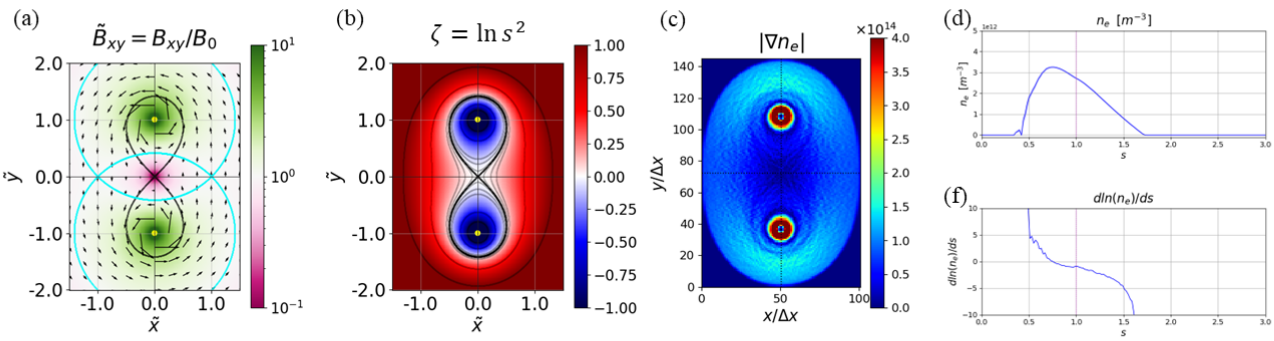

Figure 1. (a) Normalized magnetic field magnitude of the TWM, $\tilde{B}_{xy} = B_{xy}$. The figure-eight shaped black line is the separatrix field line, i.e. ζ=0. The cyan lines are of $\tilde{B}_{xy} = 1$. Magnetic field vectors circulate counterclockwise around each wire. (b) Field line value (FLV) of the TWM, ζ. Black lines are of the following FLVs: ζ=±1, ±0.5, ±0.1, ±0.05, ±0.01, 0. (c) Magnitude of electron density gradient calculated from 2D ES-PIC simulation results (d, f) Electron density gradient across magnetic field lines. The magenta dotted lines indicate the separatrix.