NUMERICAL KINETIC MODEL OF AXIAL CONFINEMENT IN A MIRROR TRAP

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Numerical kinetic model of axial confinement is developed. Simulations show that in semi-collisional regime axial losses are determined by narrow "beam" of cold ions. Analytical treatment is proposed for the case of square-well magnetic field. Simulation of the ambipolar trapping of axial losses in the intermediate collision frequency range shows that essential suppression of axial losses is possible even when ambipolar barrier is of the order of ion temperature.

I. INTRODUCTION

Numerical model is developed to study transition from kinetic to gas-dynamic regimes of axial plasma losses in a mirror trap. Influence of ambipolar potential on axial losses in the semi-collisional regime is studied numerically, while in the square-magnetic-well approximation a new analytic model of plasma outflow is also proposed. Simulations of the GDT-like axial confinement with axial losses limited by ambipolar barriers were also performed.

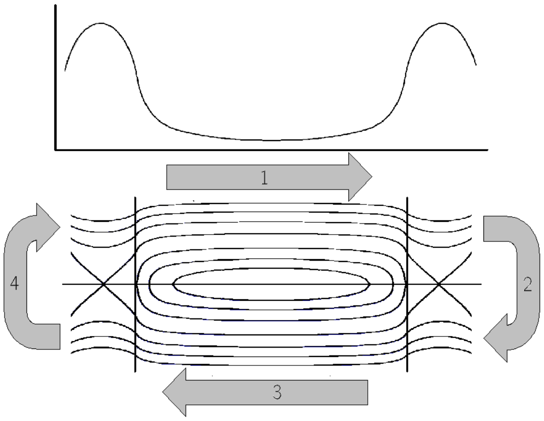

Figure 1: Magnetic field profile and ion phase plane in the mirror trap (in the Yushmanov potential $\psi = e\phi + \mu B$).

Importance of semi-collisional regimes is two-fold. First, the proposed future modifications of GDT-like devices are bound to work in this regime. Second, results of recent GDT-SHIP experiments [1, 2] need adequate explanation. Unexpectedly high level of suppression of axial losses (by a factor of 5, while the density of hot ions in the ambipolar plug exceeded the density of warm ions by a factor 1.5 only) has been observed in these experiments. It was proposed that such suppression may be explained as a result of forced transition from the gas-dynamic to kinetic loss regimes.

II. MODEL SCHEME

The code solves steady-state gyro-averaged ion kinetic equation with linearized Landau collision term:

$$v_\parallel \left(\frac{\partial f}{\partial s}\right)_{\varepsilon,\mu} = St(f) \qquad (1)$$

$$St_\mu(f) = \frac{\partial}{\partial \mu}\left(-\frac{1}{2}\,\mu\,\frac{\partial^2 g}{\partial v_\perp^2}\left(\frac{1}{B(s)}\,\frac{\partial f}{\partial \mu} + f\right)\right)$$

The short mirror-throat length and the high mirror ratio limits are assumed to simplify the problem. The first limit allows the use of collisionless kinetic equation to determine the ion distribution function in the neighborhood of each mirror throat. In the central area the collisional kinetic equation is integrated along characteristic curves on the $z - v - \mu$ grid in the narrow velocity space band containing the loss cone. The distribution of deeply trapped ions outside of the grid is assumed to be Maxwellian. Diffusion in parallel velocity can be neglected due to high mirror ratio.

The ambipolar electrostatic potential is determined by means of the quasi-neutrality condition, assuming Boltzmann distribution for electrons. The iterative procedure is employed to solve the self-consistent nonlinear problem. The iterative sequence is illustrated by the figure 1. First, equation 1 is integrated to the right in the central part region. Thereafter, collisionless equation is integrated near the right mirror throat. Then, equation 1 is integrated to the left and collisionless equation is integrated near the left mirror throat. Finally, the new ambipolar potential is calculated by means of the quasi-neutrality condition $\phi = T_e \, ln(n/n_0)$.

III. MATCHING WITH ANALYTICAL SOLUTIONS

In the gas-dynamic limit the ion losses (figure 2) match with semianalytic theory of ambipolar potential influence on the gas-dynamic plasma outflow in the short-mirror-throat case [3].

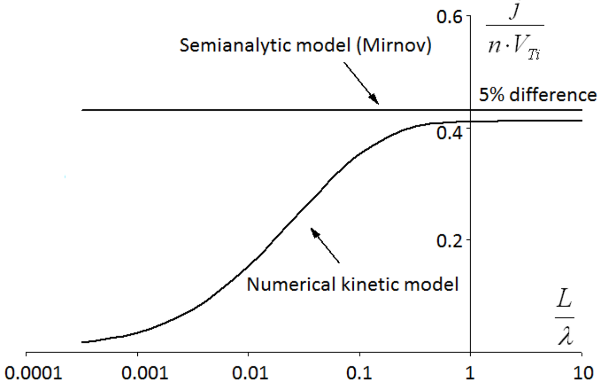

Figure 2: The ion flux through the mirror versus the collision frequency.

In the case of rare collisions with cold electrons the ambipolar potential is negligible and the calculated confinement time qualitatively agrees with the Budker's formula [4] $\tau_{conf} \sim \tau_{ii} \cdot \ln(R)$. Both the logarithmic dependence on mirror ratio and the linear dependence on collision time (figure 3) are observed as expected.

IV. INFLUENCE OF AMBIPOLAR POTENTIAL IN SEMI-COLLISIONAL REGIME

However, our main goal was to explore ion losses in semi-collisional regimes under the influence of ambipolar potential, and here we can report some interesting results.

In particular, for smooth (parabolic) plasma potential in the central plasma region there are trajectories with infinite transit time (if they are close to separatrix). Then, diffusion in transverse velocity can efficiently fill these trajectories with particles even in nearly collisionless regimes and thus produce a narrow hump (figure 4) in the ion distribution function inside of the loss cone. The characteristic width of the hump is determined by the condition $\tau_{trans} \sim \tau_{diff}$, where τ_{trans} is the transition time (depending on the profiles of the potential and the magnetic field, and the distance from the separatrix) and τ_{diff} is the time of filling the loss cone.

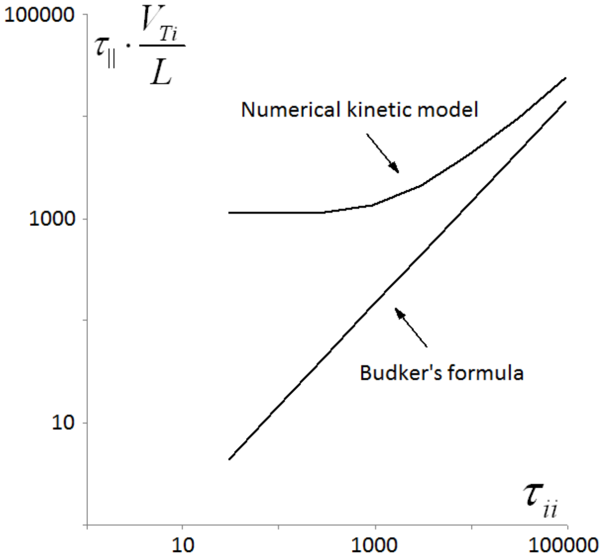

Figure 3: Dependence of the ion lifetime on the collision time.

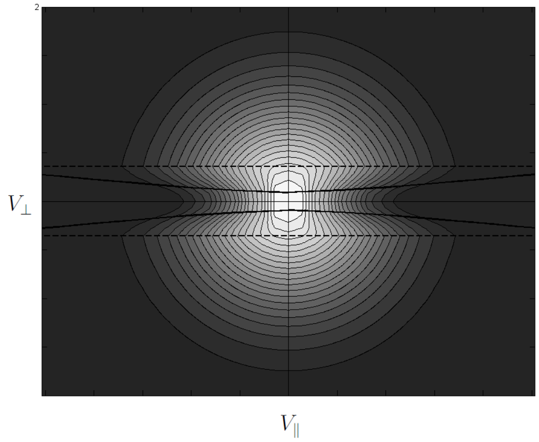

Figure 4: The distribution function in the $V_{\|}$-$V_{\perp}$ variables in the median plane of the mirror trap.

In the case of square-well magnetic field the kinetic equation can be integrated analytically. In this regime the hump itself determines the distribution of the plasma potential. A self-consistent solution with beam-like axial losses exists for high mirror ratios and not too rare collisions.

V. AMBIPOLAR TRAPPING EFFICIENCY

In the GDT-SHIP-experiment [1, 2] the axial losses were suppressed by a factor of 5, when the density of hot ions in the ambipolar plug exceeded the density of warm ions by a factor 1.5 ($L/\lambda \sim 3$). Our simulations (figure 5 a) predict suppression factor of only 1.7 for these conditions. The ambipolar trapping efficiency depends on the electron temperature, and the suppression factor increases by a factor of 2, when $T_e/T_i = 2$ (figure 5 b). It is also possible that the mismatch is related to presence of hot ions in the central cell of GDT. Besides effectively lowering the collision rate, at their mirror points the hot ions produce electrostatic humps, which can influence the outflow regime of warm ions.

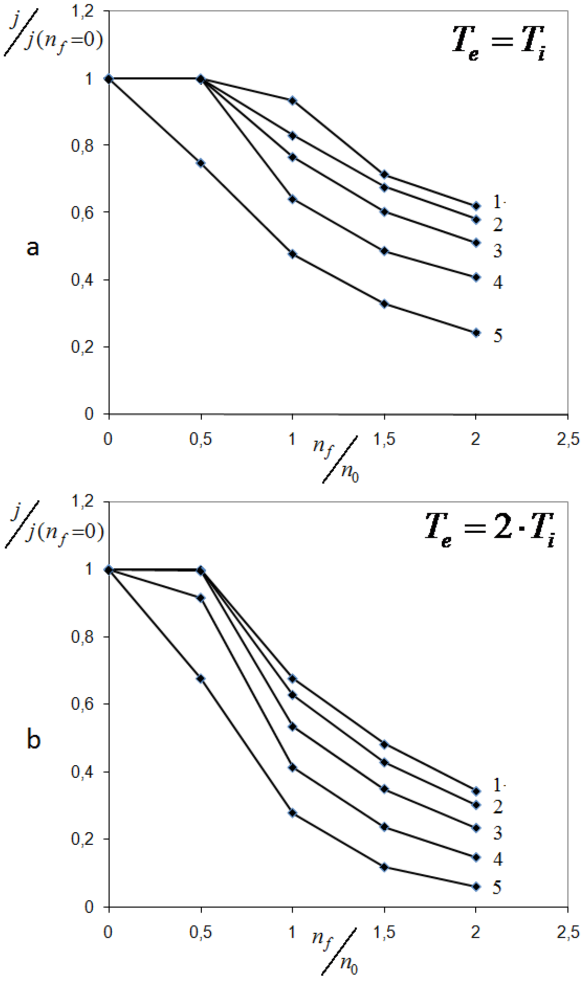

Figure 5: The ion flux suppression factor versus ratio of hot ions density to warm ions density. a) $T_e/T_i = 1$, b) $T_e/T_i = 2$.

VI. CONCLUSIONS

The numerical kinetic model of axial confinement in a mirror trap is developed. The numerical model is suitable for studying transition from kinetic to gas-dynamic regimes. Simulation results match with analytical solutions.

The influence of ambipolar potential on the axial losses in semi-collisional regime is studied. In this regime the axial losses are determined by narrow “beam” of cold ions. The analytic treatment of the phenomenon is presented. The “beam” exists at high mirror ratios and not too rare collisions.

The ambipolar trapping efficiency is studied in the intermediate collision frequency range. The simulations results do not completely match with GDT-experiment. However, it is demonstrated that essential suppression of axial losses is possible even when ambipolar barrier is of the order of ion temperature, because even such barrier is sufficient for plugging the “beam”-like losses.

ACKNOWLEDGMENTS

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