Influence of ambipolar potential on axial losses from mirror traps in semi-collisional regime

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Introduction

Axially symmetric mirrors are the most basic of all open traps. They will also be a part of most future traps as they provide excellent confinement for fast ions. There is an extensive theory covering most aspects of their physics. However, the semi-collisional regime of axial losses, when the scattering length of ions into the loss-cone is of the order of the trap length, is not described adequately.

A numerical kinetic model has been developed to study the semi-collision regime of plasma losses from a mirror trap. The model describes the transition from the kinetic regime of the losses to the gas-dynamic one. The influence of an ambipolar potential on a plasma outflow in the intermediate regime has been studied. It has been shown that in this regime the losses could be dominated by the narrow “beam” of cold ions. In the case of point mirrors this phenomenon has been analytically treated.

Again, the efficiency of an ambipolar plugging in the intermediate regime has been studied via the kinetic code. Importance of this regime is evident when considering the gas-dynamic trap GDT experiments in Novosibirsk [1]. 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 experiments with one ambipolar plug. It was proposed that such suppression is the result of forced transition from the gas-dynamic to kinetic loss regimes. 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.

Kinetic Code

The kinetic model [2] solves 1D steady-state kinetic equation for ions with Landau collisional term. A difference scheme is used to integrate the equation along characteristic curves. Short mirror length and high mirror ratio limits are used to simplify the problem. The first one allows us to use collisionless kinetic equation near each mirror. The second limit enables us to calculate a distribution function in the narrow area of velocity space which contains the loss cone. The distribution of ions outside the grid is supposed to be the Maxwellian one. Electrons are locked in the trap due to the positive ambipolar potential of plasma. Because of this, distribution of electrons is supposed to be the Boltzmann one.

Influence of Ambipolar Potential in Intermediate Regime

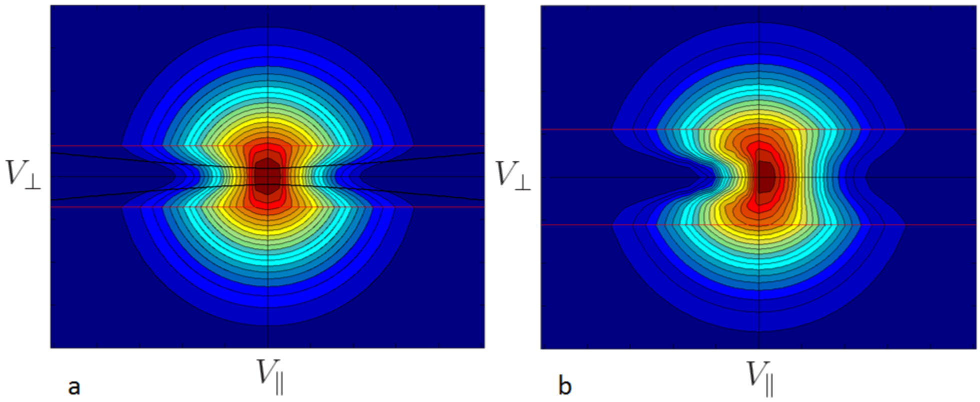

Figure 1: The distribution function in the $V_\parallel$-$V_\perp$ variables a) in the median plane b) at the $L/4$ distance from the median plane.

The influence of ambipolar plasma potential on longitudinal losses from a mirror trap was studied via the kinetic code. In the intermediate collisional range a loss cone is partially filled with ions. The value of distribution function in the loss cone is determined by the balance between the collisional diffusion of trapped ions and the outflow of ions from a trap. There is an x-point on the phase plane of particles, because of the positive ambipolar potential. For the smooth potential the transit time near separatrix tends to infinity. For this reason the trajectories near separatrix are effectively filled with particles and the narrow "beam" of cold ions arises near the x-point (figure 1).

In the case of point mirrors with flat magnetic field in the central part of a trap this regime could be treated analytically. The motion of ions in the central part is determined by the ambipolar electric field and does not depend on the adiabatic invariant μ. Therefore, the kinetic equation for transit ions could be rewritten in the form of the well-known diffusion equation.

Meanwhile, the ambipolar potential is determined by the "beam" itself in this case. The potential could be approximated by the parabolic term near the center of the trap ($\phi(Z) = -\frac{\alpha \cdot M_i \cdot Z^2}{2}$). Quasi-neutrality condition allows one to calculate the factor α:

$$\alpha \propto \frac{L}{\lambda} \cdot \frac{T_e}{T_i} \qquad (1)$$

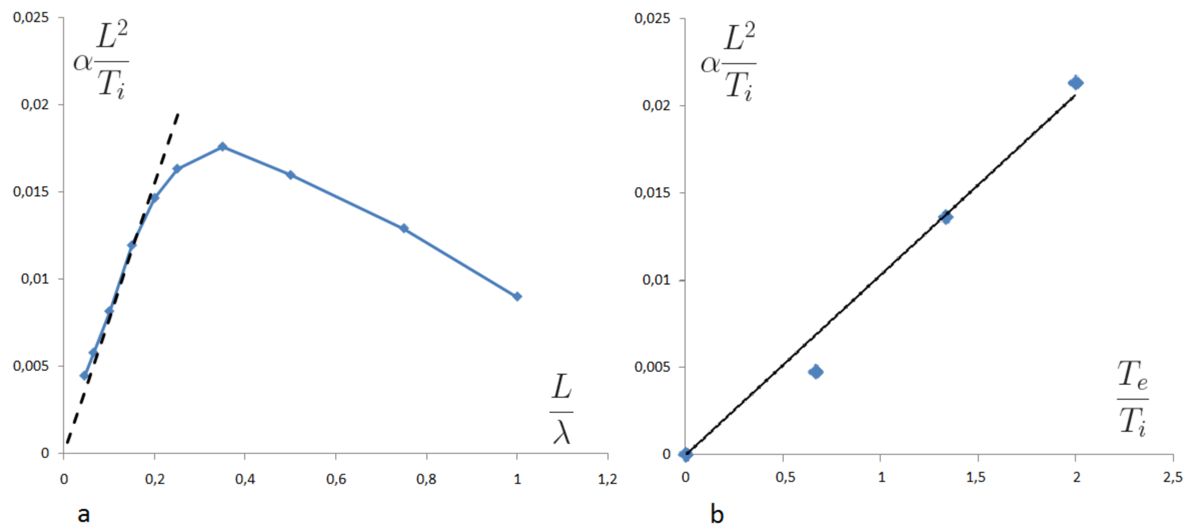

Figure 2: The second derivative of the potential in the center a) vs. a collision rate; b) vs. the temperature of electrons.

Figure 2-a shows the result of numerical modeling: the dependence of α on collision rate. When the collisions are frequent α tends to zero as expected in the gas-dynamic mode. In the intermediate range the linear dependence (1) on the collision frequency is demonstrated. Again, the linear dependence on the electron temperature predicted by the formula (1) also agrees with numerical modeling (figure 2-b).

Such regime will arise not only if the ambipolar potential is self-consistent with the "beam". If there is a population of sloshing ions produced by an inclined neutral injection (as in GDT) two humps of electrostatic potential arise near reflection points. In this case the x-points are also formed on the phase plane of transit ions and, thus, the "beam"-like regime is realized (figure 3).

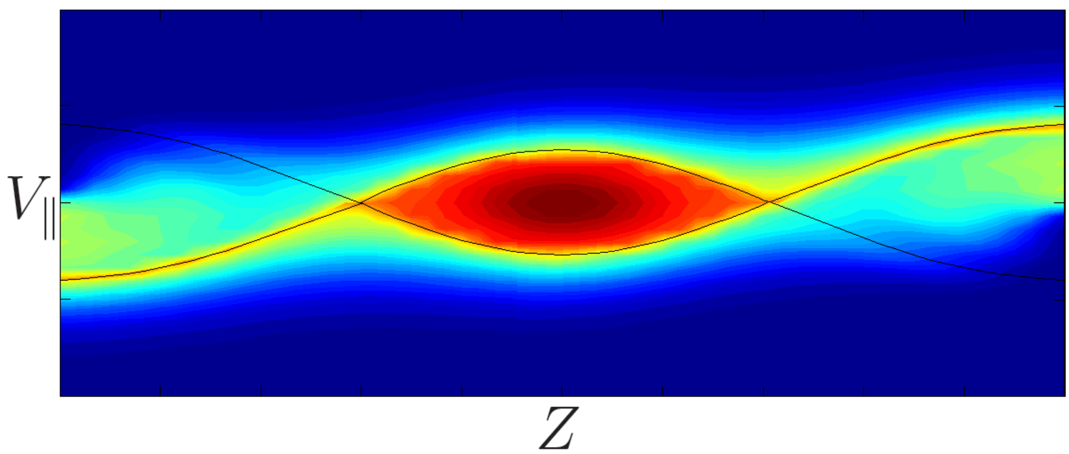

Figure 3: The distribution function in the case of two humps of the potential.

Efficiency of Ambipolar Plugging

The kinetic code was used to study the efficiency of the suppression of longitudinal losses by ambipolar plugs. It was shown that the efficiency increases in the case of rare collisions (figure 4). It could be explained by the transition from the gas-gynamic to the "beam"-like regime of losses. If ambipolar barriers in the plugs are higher then the ambipolar potential in the center of the trap the trajectories near separatrix will become electrostatically trapped. Because of this the "beam"-like losses can be locked in a trap even when ambipolar barriers are not too strong.

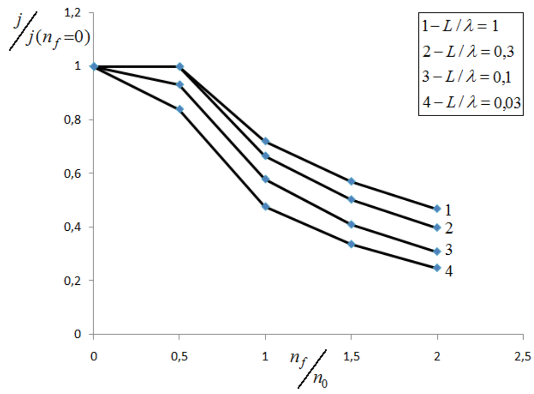

Figure 4: The ion flux suppression factor vs. the ratio of hot ions density to warm ions density in the ambipolar plugs.

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 agree with analytical solutions.

In the intermediate collisional range the "beam"-like regime of losses from a mirror trap has been discovered. The "beam" exists at high mirror ratios and not too rare collisions. In the case when the plasma potential is self-consistent with the "beam" this regime has been analytically treated. Predictions of the theory agree with numerical modeling.

The ambipolar trapping efficiency is studied in the intermediate collision frequency range. 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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References

[1] A.V. Anikeev, P.A. Bagryansky et. al., Plasma Physics Reports, **36**, 381 (2010)

[2] D.I. Skovorodin, A.D. Beklemishev, Transactions of Fusion Science and Technology, **59**, 1T, 199 (2011).