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Ion Mobility and Transport Barriers in the Tokamak Plasmas

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Abstract

The character of charged particle motion in an axisymmetric toroidal system with a constant radial electric field is investigated both analytically and numerically. Ion radial mobility caused by the combined effects of the radial electric field and charge exchange is found. A simple moment argument in the banana regime matches the simulation results well. Relation of present work and high confinement (H-mode) experiment is also discussed.

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After the first H-mode observation,[1] many experiments have been done.[2–6] It is found that the spontaneous H-mode plasmas always have sheared negative radial electric field near the plasma edge. Biased electrode triggered H-mode experiments found asymmetry behaviour between bias potential and plasma confinement.[7,8]

There are several theoretical works about the influence of radial electric field shear on the charged particle motion[9,10] and suppression of turbulence,[11–13] but the effects of radial electric field on charged particle motion deserves more attention.

The familiar equation of motion,

$$\frac{e}{m}(\mathbf{E} + \frac{1}{c}\mathbf{V} \times \mathbf{B}) = \nu \mathbf{V}$$

where ν is represents some velocity damping rate, can be solved in cylindrical coordinates, with $\mathbf{B} = B\hat{z}$, $\mathbf{E} = E_r\hat{r}$. We obtain classical radial mobility:

$$V_r = \frac{\nu}{\Omega(1 + \nu^2/\Omega^2)} V_E$$

where $\Omega = eB/mc$, is the gyrofrequency and $V_E = cE_r/B$ is the $\mathbf{E} \times \mathbf{B}$ drift velocity. Gyromotion Monte-Carlo simulation matches this result very well.

The real physics of this radial mobility is that a radial electric field in the plasma tends to drive ions in the direction of lower electric potential. Without collisions, the ions will stay in the closed orbits, the radial electric field given only a poloidal rotation due to the $\mathbf{E} \times \mathbf{B}$ drift. But with collisions, such as, charge exchange, the perturbed ions should walk along that direction and cause a radial mobility.

One thing that should be noted here is that the perturbations of electron and ion mobilities are quite different. Perturbation from electron-ion collisions can cause electron mobility[14] and the electron radial momentum can be compensated by the ion's. But neither ion-electron collisions nor ion-ion collisions can cause the ion mobility because of radial momentum conservation. The most probable perturbation for the ion mobility is ion-neutral collision, or charge exchange, which is common near the plasma edge. In this case ion radial momentum can be balanced by the neutrals.

In the toroidal geometry, the radial electric field can affect ion orbits dramatically. Figure 1 is the ion guiding center orbit calculated with different radial electric fields. We find that the negative radial electric field (inward) always tends to push the ion inward and the positive radial electric field (outward) always tends to drag the ion outward. When the radial electric field becomes very large, whether positive or negative, almost all ions become passing particles and the orbit shifts approach to zero. We can understand these orbits from the existing theory.[15,16]

For the case of weak pitch angle scattering ($\nu \ll \omega_b$, where $\omega_b = v_{||}/Rq$ is the bounce frequency, $q = rB_t/RB_p$ is the safety factor) the toroidal angular momentum is approximately still invariant

$$mR\Delta v_{||} - \frac{e}{c} B_p R \Delta r \approx 0 \ . \tag{1}$$

With total energy conservation

$$mv_{||}\Delta v_{||} + \mu \Delta B + e\phi' \Delta r = 0 \ , \tag{2}$$

and the pitch angle scattering

$$\Delta \xi = -\xi \nu \Delta t \ , \tag{3}$$

where $\xi = v_{||}/v$ is the pitch angle, we can obtain the neoclassical radial mobility:

$$V_r = \frac{\nu V_{Ep}}{\Omega_p (1 + 2V_{Ep}^2/v^2)} \tag{4}$$

with the assumption $|eE_r| \gg |\mu \Delta B/\Delta r|$. Where $E_r = -\phi'$, $V_{Ep} = cE_r/B_p$, $\Omega_p = eB_p/mc$ is the poloidal gyrofrequency.

This is consistent with the Monte-Carlo simulation results with pitch angle scattering collision operator,[17] as show in Fig. 2.

Because the orbit is the intrinsic property of the ion motion, we expect that different collision processes will not change the basic property of the ion mobility. Monte-Carlo simulation results with charge exchange collision operator shown in Fig. 3 proved our expectation.

Next we put the ions near the plasma edge, in order to study how the radial electric field affects the ion orbit loss by Monte-Carlo simulation. The result of the ion orbit loss with charge exchange collision operator under different radial electric fields is shown in Fig. 4. Simulation with pitch angle scattering collision operator gives a similar result. We find that without radial electric field the ion orbit loss is due to neoclassical diffusion caused by collisions, charge exchange or pitch angle scattering. When the radial electric field is negative, the inward ion mobility reduces the ion orbit loss significantly, and quickly stops the ion loss when radial electric field increases negatively. We can use this property to understand the transport barrier near the spontaneous H-mode plasma edge. Note that for the spontaneous H-mode plasma there is always a negative electric field near the edge. Thus the inward mobility of the ion may sharply slow down the outward ion flow, and cause the transport barrier. When radial electric field increases positively, the ion orbit loss increases very fast at first. However, when the electric field further increases, most ions become passing particles, and ion lòsses drop dramatically. When the radial electric field becomes very large, almost all ions are fixed on their original flux surface: thus the ion orbit loss tends to zero. The different mechanisms of transport barrier due to the negative radial electric field and positive radial electric field can be employed to understand the asymmetry of the bias potential and plasma confinement observed in the experiments.

In summary, an ion radial mobility due to the combined effects of radial electric field and collision with background is found both numerically and analytically. It may provide a new approach to understanding both spontaneous and biased electrode triggered H-mode.

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Figure Captions

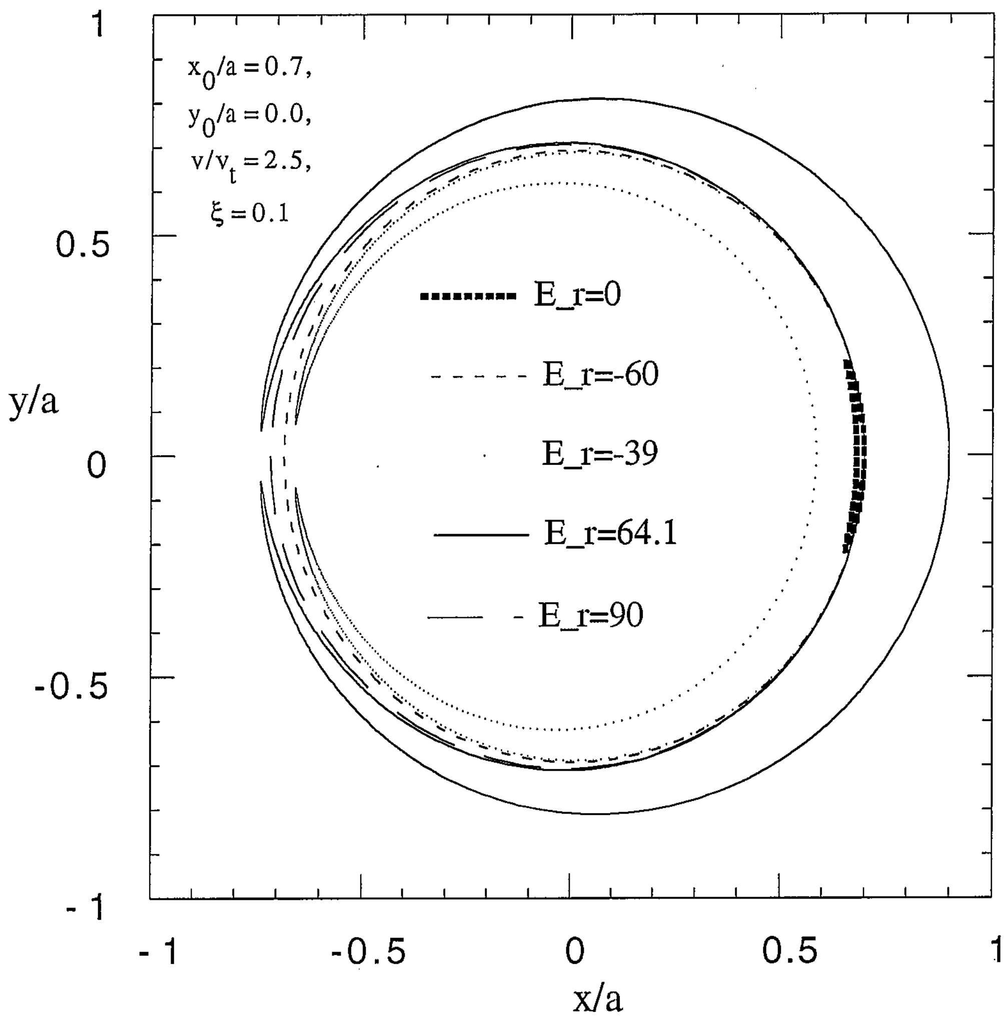
1. Ion guiding center orbits with different radial electric fields.

2. Comparison with ananytical and numerical results of ion radial mobility with pitch angle scattering. The parameters are $\epsilon = 0.2$, $q_a = 4.0$, $\rho/a = 0.002$, $r_0/a = 1/2$ and $\nu_{\rm pitch}/(v_t/R) = 0.005$, where v_t is ion thermal velocity. The radial electric field normalized to mv_t^2/ea.

3. Ion radial mobility with different radial electric fields with charge exchange collision operator, $\nu_{CX}/(v_t/R) = 0.005$.

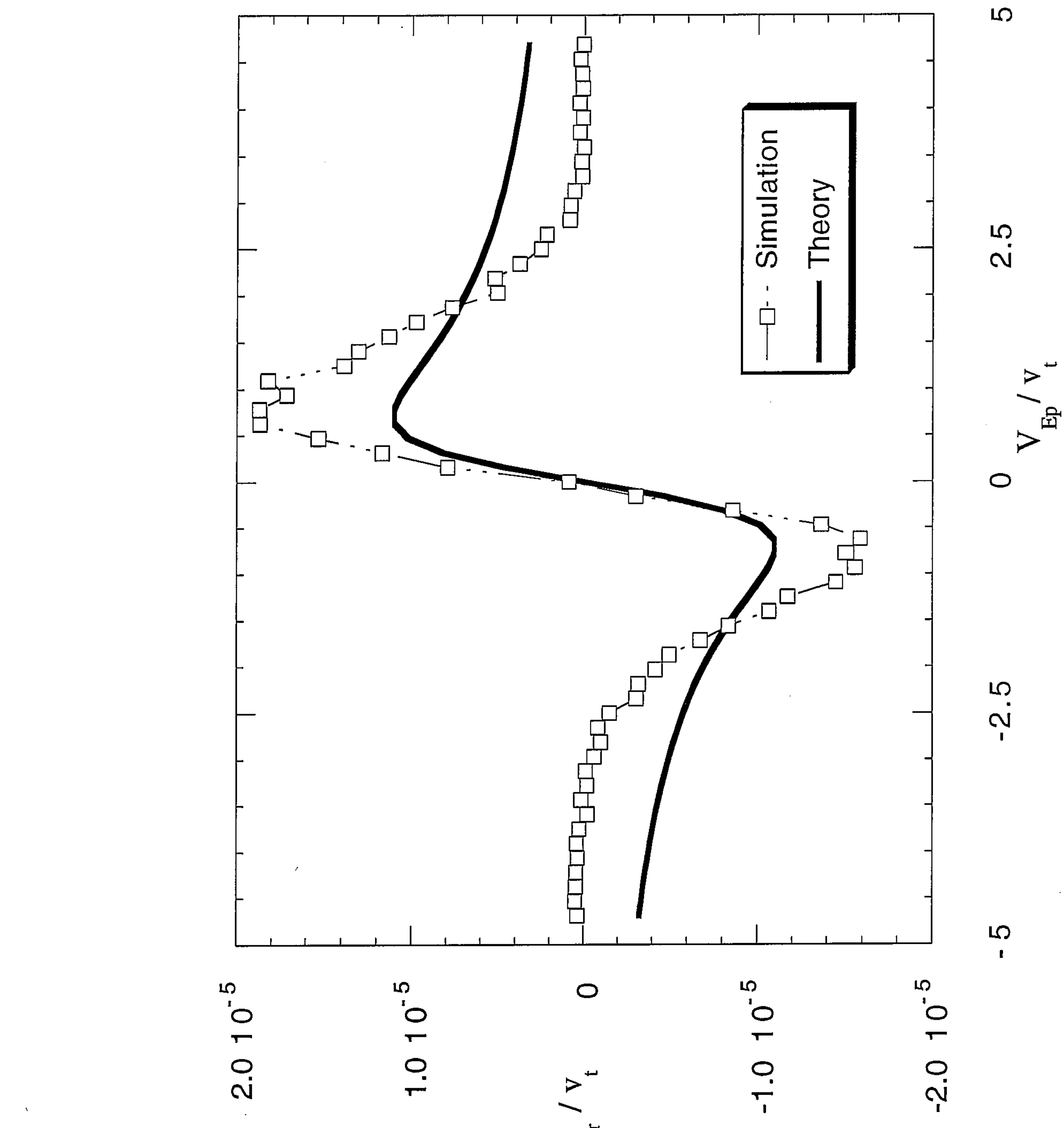
4. Ion orbit loss with different radial electric fields with charge exchange collision operator, $\nu_{CX}/(v_t/R) = 0.005$.

Fig. 1



$x_0/a = 0.7,$
$y_0/a = 0.0,$
$v/v_t = 2.5,$
$\xi = 0.1$
E_r=0
E_r=-60
E_r=-39
E_r=64.1
E_r=90
y/a
x/a
1
0.5
0
-0.5
- 1
- 1
-0.5
0
0.5
1

Fig. 2



Simulation
Theory
V_r / v_t
V_{Ep} / v_t
2.0 10^-5
1.0 10^-5
0
-1.0 10^-5
-2.0 10^-5
-5
-2.5
0
2.5
5

Fig. 3

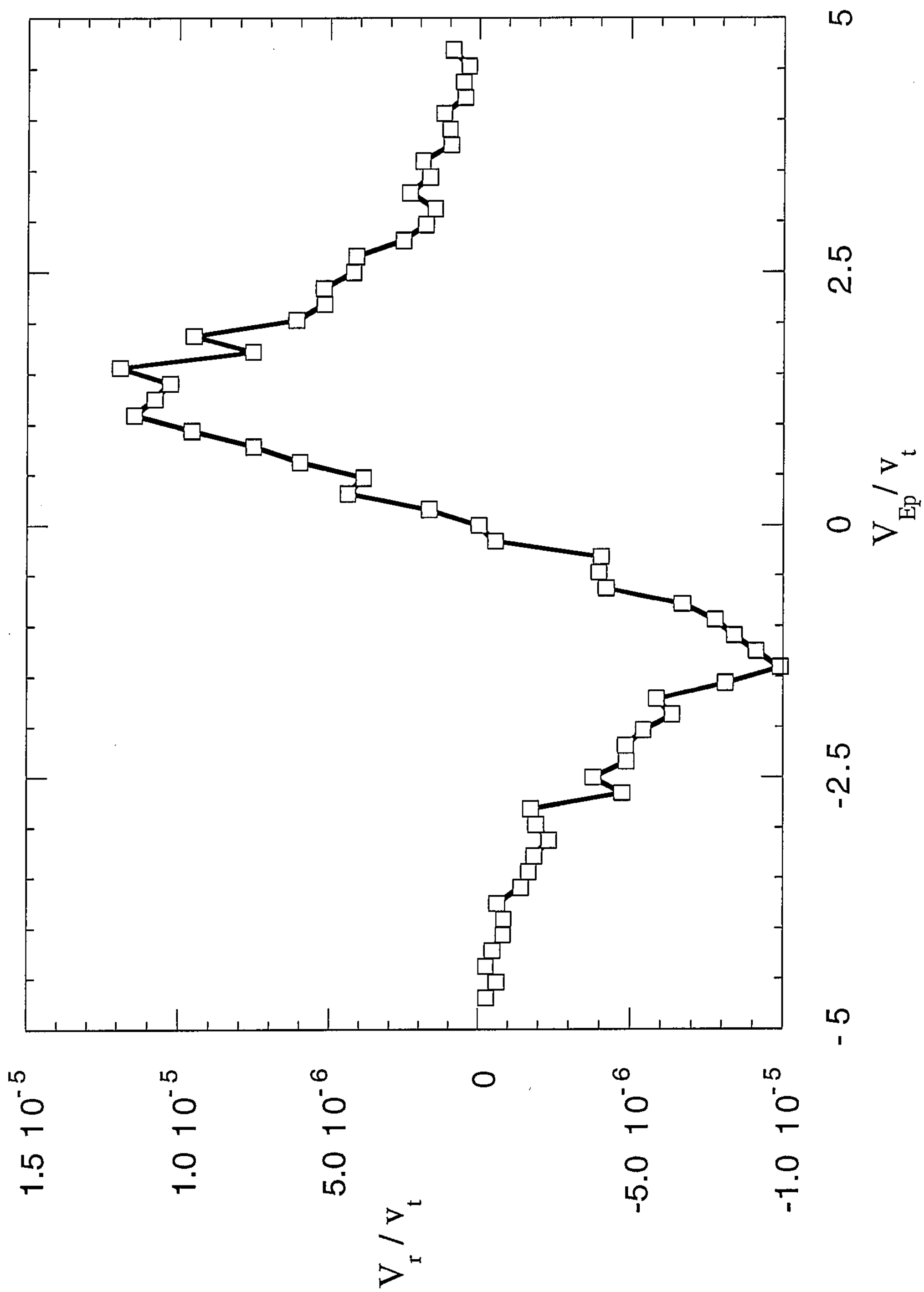
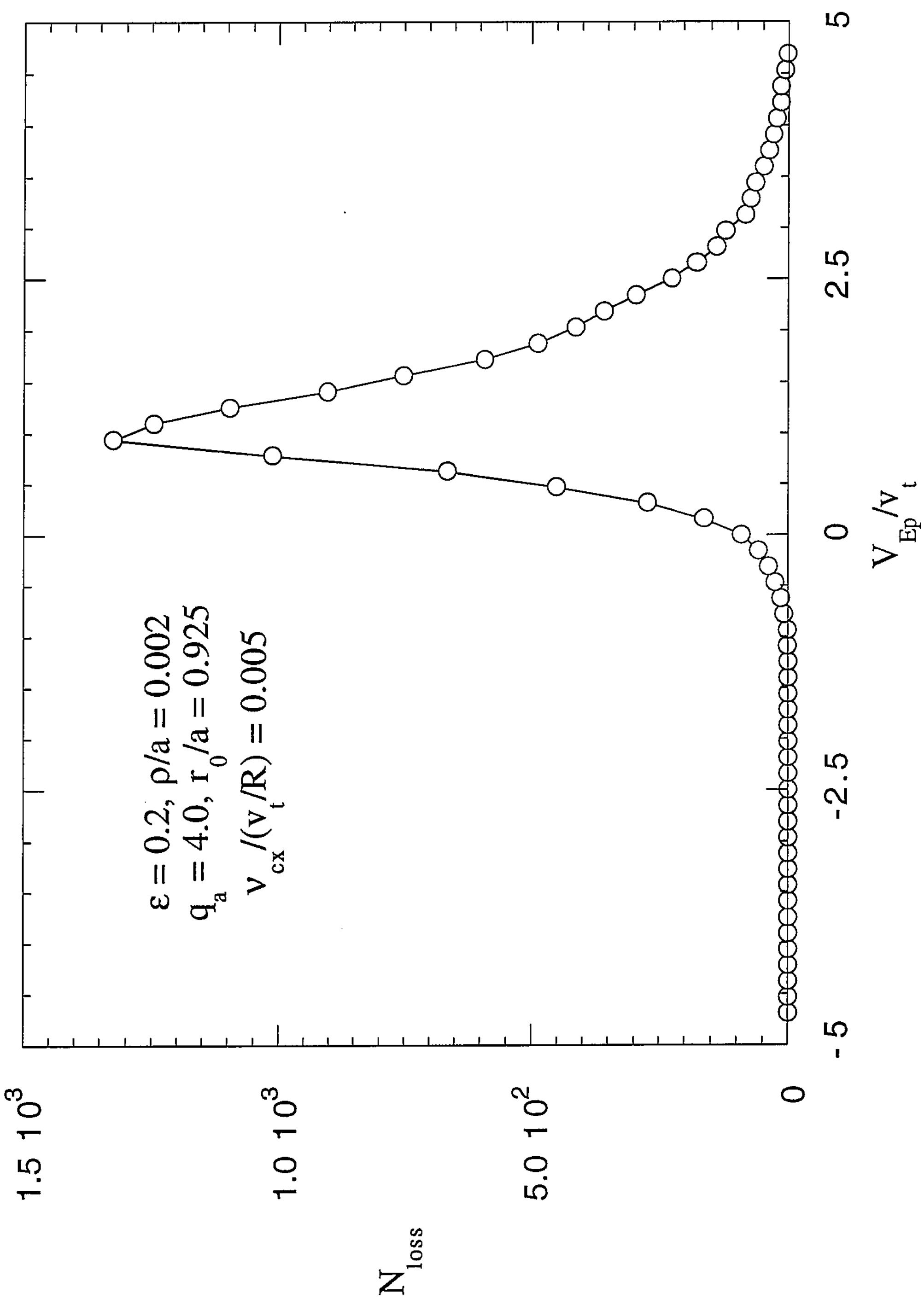


Fig. 4


ε = 0.2, ρ/a = 0.002
q_a = 4.0, r_0/a = 0.925
ν_cx/(v_t/R) = 0.005
V_Ep/v_t
N_loss
-5
-2.5
0
2.5
5
0
5.0 10^2
1.0 10^3
1.5 10^3