Potential Profile in Expander of Mirror Trap

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Abstract. The profile of electrostatic potential in the expander of mirror trap is considered. It is shown that potential drop at the wall depends strongly on distribution function of trapped electrons. Self consistent potential profile is calculated assuming Maxwell distribution of the trapped particles. Iterative numerical scheme is used to calculate the potential which holds plasma quasi-neutrality. The potential drop at Child-Langmuir sheath is governed by ambipolarity of loss along magnetic field line $j_e = j_i$. The depletion of the well between the mirror and the sheath cause increasing of the drop. The approach based on bounce-averaging is proposed to solve kinetic equation for trapped electrons.

INTRODUCTION

Axially symmetric magnetic mirrors can confine plasmas with high β and thus could be attractive as prototype neutron sources for material testing or alternative fusion reactors [1, 2, 3, 4]. Plasma losses from non-tandem mirror traps are dominated by longitudinal outflow. The ions are confined between mirrors in the inner regions of traps. However, the expander region outside determines the loss rate and recirculation of electrons. The regime of electron flow in expander strongly affects the overall energy confinement in the trap.

Mirror plasma contacts the end plate along the magnetic field lines. Therefore the electron thermal conductivity should be suppressed to limit the energy losses. The secondary emission of electrons from end plate along with ionization of neutral gas in expander region can strongly affect the confinement. Expansion of the magnetic field behind a mirror can reduce cold electrons recycling from the wall [5, 6]. Commonly plasma in a trap has positive electrostatic potential that holds the electron loss equal to the ion loss. Thus, almost all hot electrons are reflected back to the trap. If secondary electrons can penetrate the inner region of trap, the magnitude of potential barrier will be reduced to hold ambipolarity of loss. Again, if the expansion rate is high enough the secondary electrons from the wall cannot overcome the mirror due to conservation of adiabatic invariant μ.

High electric field in Child-Langmuir sheath accelerates cold secondary electrons and thus increases recycling. Taking in account high electron temperature required for fusion a potential drop at the wall can cause unipolar arcing. It was shown in [5] that scattering results in trapping of a part of the electrons between the magnetic mirror and the sheath. Presence of the trapped population moves a part of potential drop from the sheath to expander area. Qualitative examination of the filling of potential well in the expander by electrons was done previously [5, 6].

It should be noted that the expander of mirror trap is very similar to the divertor of FRC. Recently KSOL numerical code was developed to study electron dynamics in expander divertor [7]. The code solves kinetic equation for electrons on the $z - v_{\parallel} - v_{\perp}$ grid. In present work we propose an approach based on bounce-averaged kinetic equation for trapped electrons. It can allow faster computing in case of high expansion ratio.

Distribution Function in Expander

At first, let us summarize results of the Ryutov model [6]. This model uses next approximations:

- there are not cross-field losses for both electrons and ions so quasi neutrality constraint assumes ambipolarity of loss along magnetic field lines;

- the case of weak collisions is considered;
- for simplicity, ions velocity variation is neglected so $n_i \sim \frac{1}{R}$ (where R is the expansion ratio of magnetic field);
- secondary electrons emission is neglected.

The potential of plasma is governed by quasi-neutrality constraint which means one electron is lost from the trap per one ion. So electrostatic potential barrier $-\varphi_w$ (let us take the zero of potential φ to be at the mirror) of order of $\frac{T_e}{e} log\sqrt{\frac{m_i}{m_e}}$ should be formed between the mirror and the wall to hold electron loss equal to ion loss. At the same time the potential profile along the magnetic field depends on electrons distribution function. In vicinity of the mirror while $-e\varphi \ll -e\varphi_w$ distribution is close to Maxwell-Boltzmann one. Thus, quasi-neutrality equation $n_i = n_e = exp\left(\frac{e\varphi}{T_e}\right)$ gives:

$$\varphi \approx -\frac{T_e}{e} log(R) \tag{1}$$

If φ becomes comparable with φ_w distribution function is far from Maxwell one. In this region there are three populations of electrons: electrons transiting from the mirror to the wall, electrons reflected from potential barrier and electrons trapped between the potential barrier and magnetic mirror. The fact is that total density of transiting and reflecting electrons is not enough to hold quasi-neutrality if φ is close to φ_w. Thus the density of trapped electrons have to be high enough to match with ions density. As the depth of the potential well is of order of the sheath the density of trapped electrons dominates potential drop at the wall. The approximate model of Ryutov is based on assumption that the value of distribution function of trapped electrons is of order of distribution of transiting electrons. The kinetic equation should be solved to exactly calculate distribution function of trapped electrons.

Trapped electrons

In drift approximation the longitudinal motion of electrons in governed by well known effective Ushmanov potential:

$$\Psi = -e\varphi + \mu B \tag{2}$$

where μ is adiabatic invariant. Let us consider schematic profile of electric potential in expander of the trap shown in Fig. 1. As $R(z)$ is one-to-one function in expander region we use R as coordinate along magnetic field line instead of z. The profile shown on the Fig. 1 is logarithmic one with the sheath at the wall.

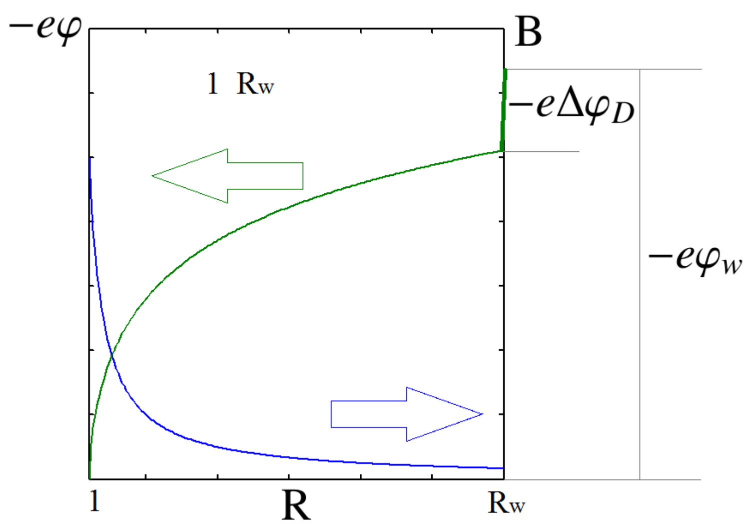

FIGURE 1. Schematic profile of electric potential in expander region of the trap.

Considering phase portrait of electrons on the plane $R - v_{\|}$ with $\mu = 0$ we obtain two populations of electrons: transiting to wall and reflected by total potential drop $-e\varphi_w$. In case of $\mu \neq 0$ the portrait is more complicated because electrons also could be reflected from the mirror. The case of not very high μ is illustrated on the Fig. 3 (a). In this case the potential well is formed but $\Psi(R_w)$ is still higher than $\Psi(1)$. So the area of trapped electrons is surrounded by area of reflecting electrons. Collision should result in filling the well by scattered electrons. If μ is high enough that $\Psi(R_w) < \Psi(1)$ the trapped area moves to the wall. In this case the energy of electron on the separatrix is less then the value of effective potential at the mirror. Thus there are not reflected electrons and trapped area is separated from the transiting particles by empty gap. In general we should consider the phase volume of trapped particles in the $R - v_{\|} - \mu$ space. The collisions results not only in filling this volume by electrons but also in depletion through the boundary at high μ.

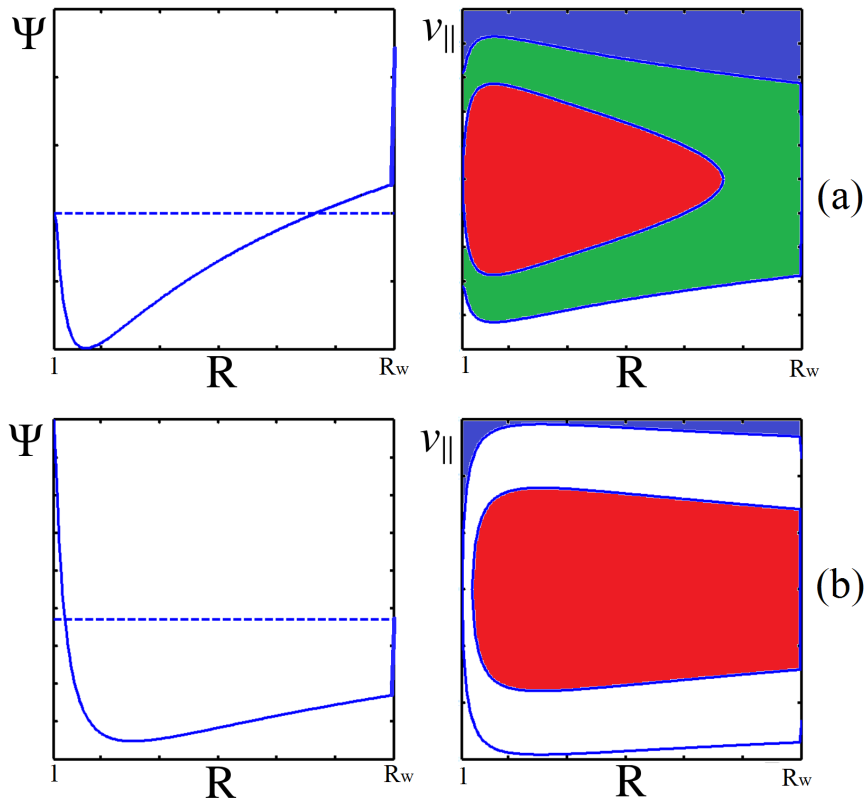

FIGURE 2. Left figure illustrates effective potential $\Psi = -e\varphi + \mu B$ as function of expansion ratio R. (b) Right figure shows phase plane $R - v_{\|}$. Red, green and blue areas correspond trapped reflected and transiting electrons. (a) is the case of low μ, (b) is the case of high μ.

Potential Profile

Let us examine the influence of the trapped electrons density on the potential profile in the expander region. Further we use simplified model based on approximations of the model of Ryutov. Namely, we assume that the areas of trapped, reflected and transiting electrons is filled by Maxwell distribution according expression:

$$f_M = n_m \left(\frac{m_e}{2\pi T_e}\right)^{\frac{3}{2}} exp\left(-\frac{m_e v_{\|}^2}{2T_e} - \frac{\mu B}{T_e} + \frac{e\varphi}{2T_e}\right), \tag{3}$$

while remaining phase space is empty. Iterative numerical scheme is used to calculate the potential which holds plasma quasi neutrality. The potential drop at the sheath is governed by ambipolarity of loss along magnetic field line $j_e = j_i$.

Figure 3 shows potential profile in case of $R_w = 100$. Although the expansion ratio is higher then $\sqrt{\frac{m_i}{m_e}} \approx 40$ the profile is still close to the logarithmic one $\varphi \sim log(R)$. The red line shows results of calculations with the value of distribution of trapped electrons reduced by the factor of 2. It results in significant increasing of the the sheath. Further we are planning to use bounce-averaged kinetic equation to accurately calculate the phase space density of trapped electrons.

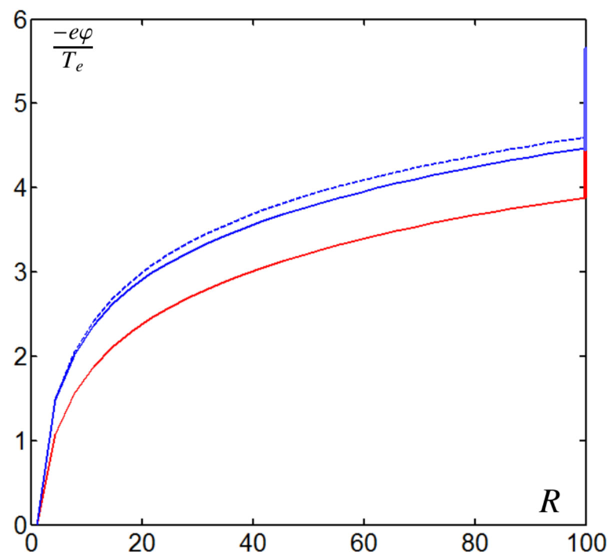

FIGURE 3. Calculated potential profile in expander. Blue line corresponds Maxwell distribution of trapped electrons, red line corresponds reduced value of distribution by the factor of 2, dashed line represents $log(R)$ dependency.

CONCLUSIONS

Self consistent calculations of potential profile based on assumption of Maxwell distribution of the trapped particles is presented. It is shown that potential drop at the wall depends strongly on distribution function of trapped electrons. The depletion of the well between the mirror and the sheath cause significant increasing of the potential drop at the wall.

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