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A Single Minimum-B Ambipolar Trap

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A design of a single minimum-B ambipolar trap is proposed. This ambipolar trap has the plug and thermal barrier potentials at both end mirror cells created by electron cyclotron resonance heating only. The plasma radial transport is suppressed by a magnetic well in the central mirror cell of the ambipolar trap, while a transport is enhanced by the azimuthally nonuniform electrostatic potential in the end cells.

The conventional ambipolar trap such as GAMMA10 (PRC Univ.Tsukuba, in Japan) has an axi-symmetric central region and re-circularized magnetic configuration as a whole in order to suppress the ion neoclassical radial transport. However the experimental results indicate that the radial loss of plasma is not small.[1] Therefore a new design for an ambipolar trap with an inherent feature of small transport of plasma is required.

It is known that an open trap does not have any magnetic surfaces because magnetic field lines are open. The electrons, therefore, can have a different distribution function on each magnetic field line, which leads to a non-axisymmetric electrostatic potential. In the typical parameters of an open trap, $\boldsymbol{E} \times \boldsymbol{B}$ drifts of ions and electrons are faster than ∇B drifts. So the equilibrium state is realized along each equi-potential surface.

Figure 1 illustrates a variation of equi-potential surfaces on a cross section in the magnetic mirror cell. The circular equi-potential surfaces are assumed at first in Fig.1(a). Ions and electrons are produced by ionization process in the mirror cell, and begin to drift by ∇B-drifts in the opposite direction according to the opposite charge of ion and electron. If the non-uniform ionization occurs, the charge separation of ions and electrons leads to a deformation of equi-potential surfaces as shown in Fig.1(b). The new equilibrium state is realized on each resultant deformed equi-potential surface in an open trap.

If the shape of mod.B surface cross to an axis (a magnetic field line axis) is not the same as that of the equi-potential surface, the ions diffuse radially through neo-classical transport process. If the non-axisymmetricity of an equi-potential surface changes along a magnetic field line, ions and electrons move radially across the equi-potential surfaces through $\boldsymbol{E} \times \boldsymbol{B}$ drifts as well as ∇B drifts.

A single minimum-B ambipolar trap is designed to suppress ion and electron radial diffusions under the circumstances where non-axisymmetric electrostatic potential (azimuthally nonuniform electrostatic potential) exists in an open trap.[2] Essential idea is given in the following. The particle energy ε and magnetic moment μ are assumed to be conserved during its motion. A particle repeats a bounce motion along a magnetic field line, where the relation of $\varepsilon = \mu B_t + e\varphi_t$ holds at the turning point, and drifts across the equi-potential surface. Here B_t is the magnitude of magnetic field at the turning position and $e\varphi_t$ is a potential energy there. If the particle has an energy $\varepsilon \gg e\varphi_t$, i.e., $\varepsilon \simeq \mu B_t$ is satisfied, the magnetic field B_t is regard as a conservative quantity.

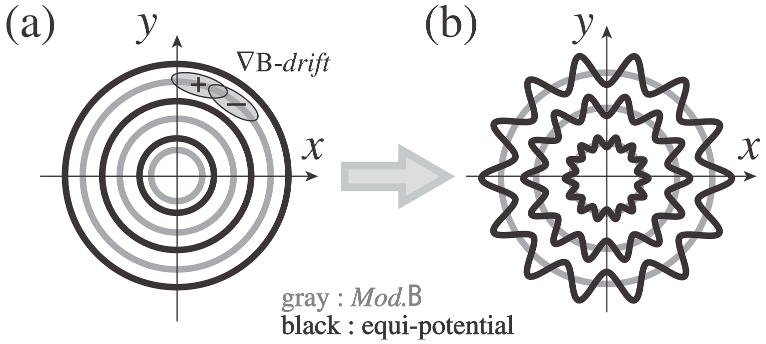

Figure 1: Schematic diagram of mod.B and equi-potential surfaces. (a) is the circular case and (b) is the case added the perturbation to the equi-potential surfaces

The minimum-B open trap has a closed mod.B surface so that the particle motion is restricted within $B(x, y, z) \leq B_t$, that is, confined radially even in the non-axisymmetric electrostatic potential. The axial confinement of the open trap is improved by creating a plug and thermal barrier potentials in the end mirror cells located at both ends of the open trap. Here end cells are designed to have an open mod.B surface so that ions trapped in the thermal barrier potential are expected to drift out radially.

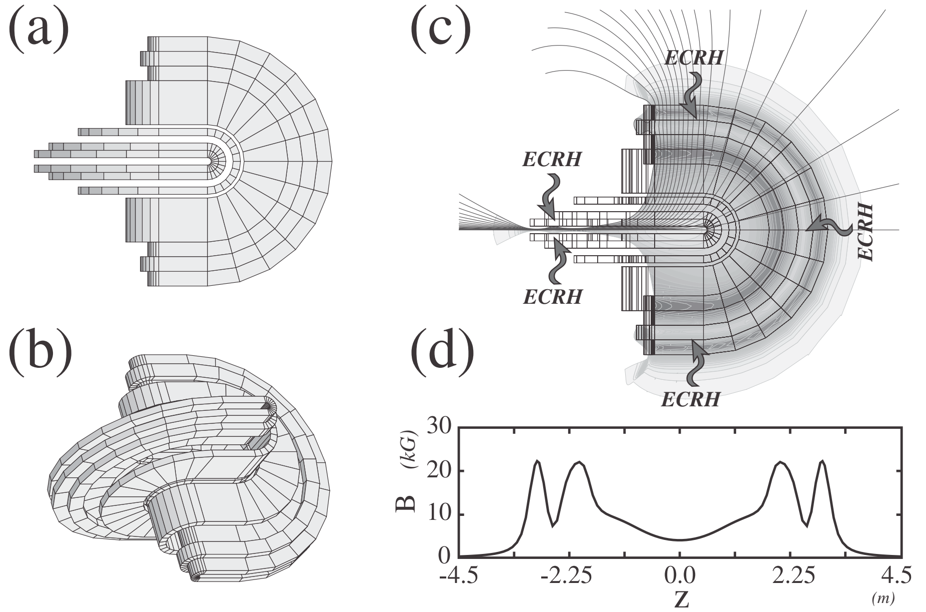

Figure 2: Schematic diagram of a single minimum-B ambipolar trap. (a) is a top view and (b) is a bird's eye view of coil system. (c) is Mod.B surfaces and magnetic field lines in a single minimum-B ambipolar trap (c) and axial profile of magnetic field (d).

Figure 2 illustrates a single minimum-B ambipolar trap. A coil system is shown in Figs.2(a) and 2(b). The coil system makes a multiple mirror magnetic field configuration in Figs.2(c) and 2(d), where a central mirror cell consists of a minimum-B magnetic field and two end-mirror cells located at both side of the central cell which are an open mod.B but not minimum-B. The ions and electrons trapped in the central cell are confined radially by a magnetic well, but those trapped in both end cells are lost radially in the nonuniform electrostatic potential.

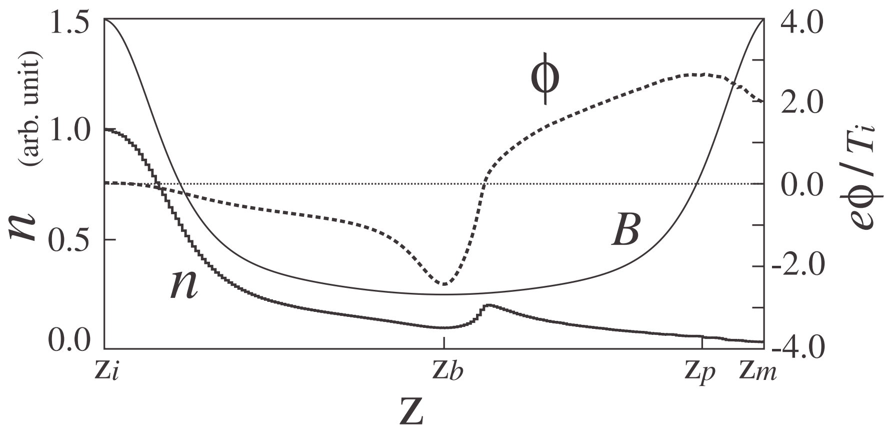

Figure 3: Profiles of an electrostatic potential (dashed line) and ion density (bold solid line) along a magnetic field line (solid line), which was obtained by a Monte Carlo simulation in Ref.3.

The larger ion and electron radial losses are used to make a plug and a thermal barrier electrostatic potential formation in the end cells. To see the electrostatic potential profile along a magnetic filed line, a Monte Carlo simulation result is plotted in Fig.3. Although a detailed information on the electrostatic potential formation will be found in Refs.[3-5], a brief review is given in the following. The distribution function of electrons trapped in the end-mirror cell is assumed as $f_e = \frac{n_{ec} m_e^{3/2}}{(2\pi)^{3/2} T_{e\parallel}^{1/2} T_{e\perp}} \exp\left\{-\frac{m_e v_\parallel^2}{2T_{e\parallel}} - \frac{m_e v_\perp^2}{2T_{e\perp}} + \frac{e(\varphi_b - \varphi_i)}{T_{e\parallel}}\right\}$ at $z = z_b$. This electron distribution function f_e is bi-Maxwellian with two component temperatures $T_{e\parallel}$, $T_{e\perp}$ parallel and perpendicular to the magnetic field line. So a modified Boltzmann law can be obtained as $e\Big(\varphi(z) - \varphi_b\Big) = T_{e\parallel} \ln\left\{\left[\frac{T_{e\perp}}{T_{e\parallel}} + \left(1 - \frac{T_{e\perp}}{T_{e\parallel}}\right)\frac{B_b}{B(z)}\right]\frac{n_e(z)}{n_{eb}}\right\}$, where the subscript b denotes the quantity at $z = z_b$. This type of modified Boltzmann law can create the plug and thermal barrier electrostatic potential profile shown in Fig.3. In order to obtain the electrostatic potential profile along a magnetic field line, the effect of Coulomb collision of ions is necessary further more.

The procedure to determine the electrostatic potential along a magnetic field line is the same as that of a presheath potential. That is, some dissipation such as Coulomb collisions or ionization effects is included in ion kinetic motions and electron motions are included in a modified (or traditional) Boltzmann law, in order to obtain the electrostatic potential in front of the sheath potential.

Therefore, the axial confinement of the ambipolar traps is improved by the plug and thermal barrier potential formations by electron cyclotron resonance heating only, the formation mechanism of which is understood that an electron distribution function in the end-mirror cells are non-Maxwellian and a small amount of ion Coulomb collisions exists there.[3-5] That is, non-Maxwellian electrons can generate easily the axial potential variation in an open trap.

In order to obtain a high plug potential, the deeper thermal barrier potential and the higher ratio of $T_{e\perp}/T_{e\parallel}$ are required.[4] As mentioned previously in this paper, the single minimum-B ambipolar trap has an open contour surface of mod.B in the end cell, i.e., not minimum-B there. Therefore a large amount of ion and electron radial transport is expected in the end cells due to azimuthally nonuniform electrostatic potential in the end cells.

In summary, we have shown a single minimum-B ambipolar trap which is expected small plasma loss from the confining central cell region. The volume of a confining central cell region is not so large to the single minimum-B ambipolar trap. Therefore a design of a linked minimum-B ambipolar trap is under consideration as a next step.

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[4] I.Katanuma, Y.Tatematsu, K.Ishii, T.Saito, K.Yatsu; Phys. Plasmas, in press (2002).

[5] I.Katanuma, Y.Tatematsu, K.Ishii, T.Saito, K.Yatsu; in preparation (2002).