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A New Design of a Tandem Mirror

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Abstract

Tandem mirror experiments have proved that the plug potential is created by $\omega_{ce}ECRH$ only, where ions and electrons in the central cell have been confined axially well. On the other hand the radial loss of plasma in a tandem mirror has lately drawn considerable attention. Therefore, we are designing a new tandem mirror improving axial and radial confinement of plasma.

Keywords:

design, tandem mirror, radial transport, electrostatic potential

1. Introduction

Tandem mirror experiments have proved that the plug and thermal barrier potentials are created successfully by $\omega_{ce}ECRH$ only. Ion axial confinement has been improved greatly by the plug potential. The physical mechanism, which remained unknown for a long time, has been found by ourselves recently [1-3]. That is, the non-Maxwellian electron distribution function in the plug/thermal barrier region, two-component electron distribution function in the central cell, and ion coulomb collisions are required for the plug and the moderately deep thermal barrier potential formations [1].

However, the tandem mirror experiments have revealed the existence of a larger plasma radial transport in the plug/thermal barrier region. In the thermal barrier region the plasma density is considerably lower than that in the central cell. This large radial transport exists even in the axisymmetric end-mirror cells such as the GAMMA10 tandem mirror [4]. Therefore the radial transport is considered not to come from a non-axisymmetric magnetic field such as a neoclassical transport (axisymmetric electrostatic potential + non-axisymmetric magnetic field). As the radial loss may extend to the central cell in a tandem mirror, we are designing the tandem mirror improving the radial and axial plasma confinement.

2. On the Radial Transport

The mechanism of a large radial transport in the thermal barrier region of a tandem mirror is unknown at present. However the transport is accompanied with $\omega_{ce}ECRH$, so that the most plausible mechanism is supposed as follows.

There is no magnetic flux surface in the open-ended system such as a tandem mirror. Noting that the relation $\omega_{b\parallel} \gtrsim \omega_{E\times B} \gg \omega_{\nabla B}$ holds in the present tandem mirror, the equilibrium state is realized along each magnetic field line firstly. Here $\omega_{b\parallel}$ is the bounce frequency along a magnetic field line, $\omega_{E\times B}$ and $\omega_{\nabla B}$ are the bounce frequencies due to the $\boldsymbol{E} \times \boldsymbol{B}$ drift and $\nabla \boldsymbol{B}$ drift in the azimuthal direction, respectively. In the next stage the equilibrium state will be realized along each equi-potential surface due to the $\boldsymbol{E} \times \boldsymbol{B}$ drift. The $\nabla \boldsymbol{B}$ drift is much smaller than the $\boldsymbol{E} \times \boldsymbol{B}$ drift. The discrepancy between the equi-potential surface and the Mod-B surface makes a particle feel an effective non-axisymmetric magnetic field, which causes the neoclassical transport (non-axisymmetric electrostatic

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potential + axisymmetric magnetic field).

Figure 1 displays the mechanism of generating the discrepancy between the equi-potential surface and the Mod.B surface even in an axisymmetric magnetic mirror. Firstly, the equi-potential surface is assumed circular as shown in Fig. 1. In general, plasma equilibrium state is realized on the equi-potential surface. The ionization, however, occurs non-uniformly, on the cross section surrounded by the equi-potential surface. The ionized ions and electrons drift in the opposite azimuthal directions to each other due to $\nabla \boldsymbol{B}$ drifts as shown in Fig. 1. The resultant charge separation does not lead to the outward plasma drift because the mirror system is assumed to have an average minimum B magnetic configuration to assure MHD stability. Instead, the high-m modes appear on the equi-potential surfaces.

Ions and electrons drift along a winding equi-potential surface in Fig. 1. The $\nabla \boldsymbol{B}$ drifts cause the ion and electron motions across the winding equi-potential surfaces, where the orbits become chaotic in case of a large amplitude of the high-m mode on equi-potential surfaces [5]. Therefore, a large radial transport of plasma is anticipated.

3. Concept of a New Open-ended System

In the previous section we have mentioned that a large radial transport is expected when $\omega_{b\|} \gtrsim \omega_{E\times B} \gg \omega_{\nabla B}$. The relation of $\omega_{E\times B} \gg \omega_{\nabla B}$ exists in the case of high T_e, that is, when plasma heating such as ECRH and ICRF is introduced in the operation.

It is necessary to suppress the large radial transport even in the configuration of Fig. 1. Ions and electrons drift radially through $\boldsymbol{E} \times \boldsymbol{B}$ drifts and $\nabla \boldsymbol{B}$ drifts, where energy ε and magnetic moment μ of a particle are conserved during its drift. At the axial turning point of a particle the energy and magnetic moment satisfy the relation $\varepsilon = \mu B_t + q\varphi_t$, where B_t and φ_t are the magnetic field and electrostatic potential at the turning point. If the relation $\mu B_t \gg |q\varphi_t|$ is satisfied, the magnitude B_t is conserved during the drift.

Because the Mod-B surface is open in the axisymmetric magnetic mirror while the surface is closed in the minimum B magnetic configuration, the minimum B magnetic configuration can confine the particles within the Mod.B surface even in the equi-potential surface such as Fig. 1. The magnetic field is local minimum at the center of the minimum B magnetic configuration so that the Mod-B surfaces are closed around the center.

4. Single Minimum *B* Tandem Mirror

The minimum B magnetic configuration has a great benefit to the plasma radial confinement even in the case that the winding equi-potential surfaces appear such as that in Fig. 1. The drift orbits of ion and electron are restricted within the surface satisfying $B(x,y,z) = B_t$.

Figure 2 shows the schematic diagrams of the single minimum B tandem mirror coils. The magnetic field is plotted in Fig. 3, where the magnitude of magnetic field is displayed in shading in Fig. 3(a) and the magnetic field on axis is plotted in Fig. 3(b). The central cell of the tandem mirror is inside the inner mirror throat and the plug/thermal barrier region is between the inner and outer mirror throats. The mirror ratio of magnetic field at the inner mirror throat to that at the midpoint of the central cell is about six in Fig. 3.

The micro-wave, indicated by ECRH in Fig. 3(a), is injected around the midway from the thermal barrier to the outer mirror throat and creates the plug potential by heating electrons there [1]. The end-mirror cell has the open contours of magnetic field so that the ions trapped in the end mirror cell drift out radially. The

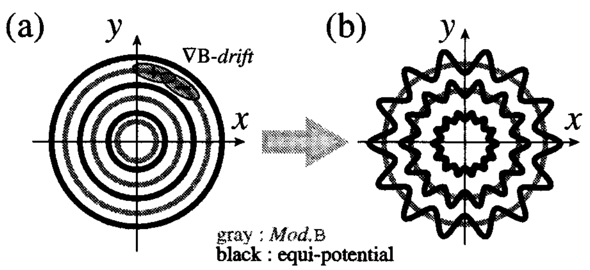

Fig. 1 Schematic diagram of equi-potential surfaces in an axisymmetric mirror, and mechanism of generating the high-*m* modes on equi-potential surfaces.

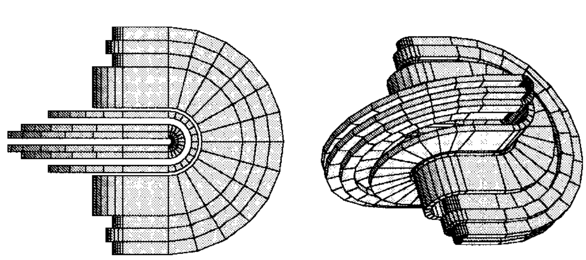

Fig. 2 Schematic diagram of single minimum *B* tandem mirror coils, where left figure is a top view and right figure is bird's eye view.

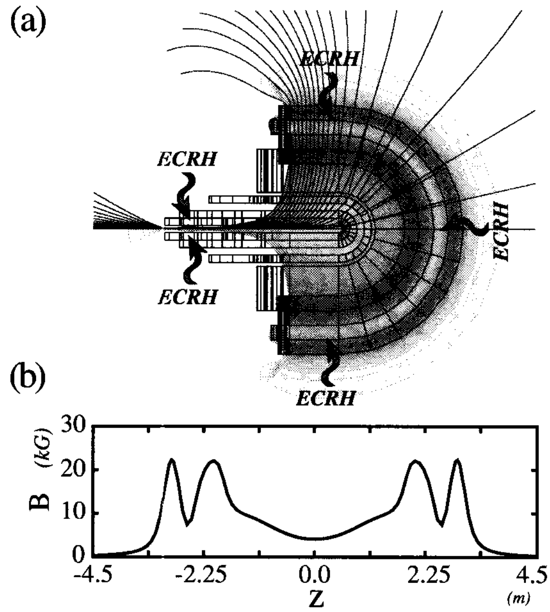

Fig. 3 Magnetic field configuration. (a) is magnetic field lines and contours of magnitude of magnetic field. (b) is the magnetic field on axis.

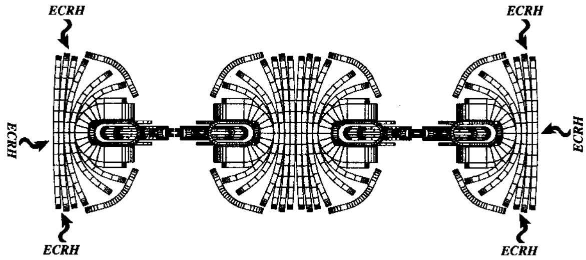

Fig. 4 Schematic diagram of linked minimum *B* mirror coils.

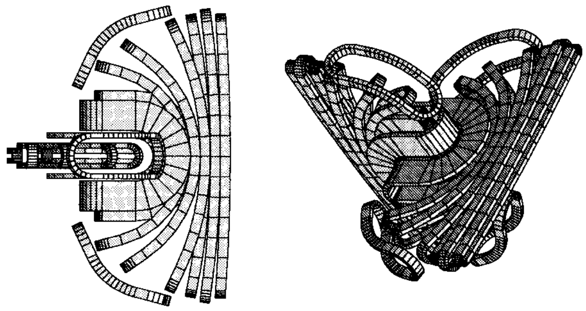

Fig. 5 Schematic diagram of each component of linked minimum *B* mirror coils, left figure is a top view and right figure is bird's eye view.

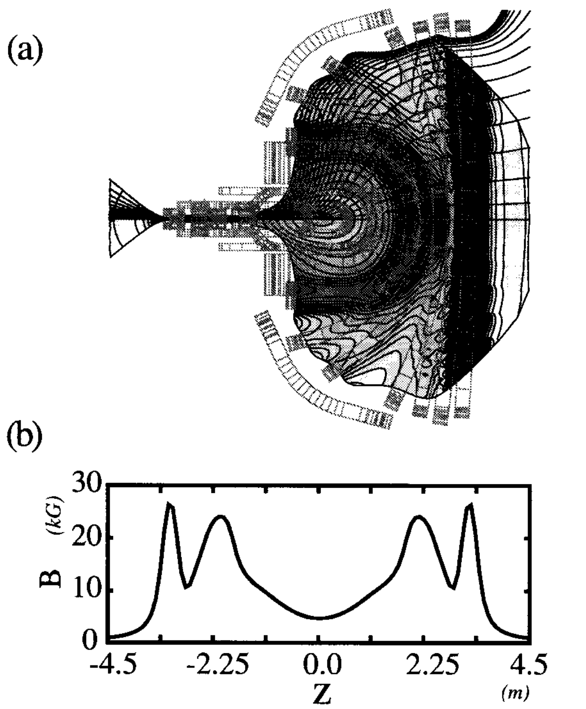

Fig. 6 Magnetic field configuration. (a) is magnetic field lines and contours of magnitude of magnetic field in each component of linked minimum *B* mirror coils. (b) is the magnetic field on axis.

thermal barrier potential, therefore, are created and so the electrons are confined within the minimum *B* central cell magnetically and electrically.

The weak point of this single minimum *B* tandem mirror is that the volume of the central cell is rather small in Figs. 2 and 3, so that input power (ECRH) to create the plug potential may be expensive per the unit volume confining plasma.

5. Linked Minimum *B* Mirror

The linked minimum *B* is designed in order to make the volume of the central cell region larger and to gain the power efficiency in Fig. 4. The essential part of the linked minimum *B* mirror is to link the single minimum *B* tandem mirror in a line, where Fig. 4 is an example set four unit single minimum *B* mirrors in a line. The plug and thermal barrier potentials are created in the outermost end mirror cells by ECRH as shown in Fig. 4. The injected power (ECRH), therefore, is required only in the outermost mirror cells, which improves the power efficiency compared to the single minimum *B* tandem mirror.

Each component of the linked minimum *B* mirror is shown in Fig. 5, where the coils are plotted. The coil system is more complicated than that of Fig. 2 in order that the outermost magnetic field lines are bended to link to the neighbor mirror cell as can be seen in Fig. 6, where the equi-contour surfaces of magnetic filed are drawn in Fig. 6(a) and the magnetic field on axis is plotted in Fig. 6(b). The mirror ratio of magnetic field at midpoint of central cell of each component to the inner mirror throat of each component is about six.

The ions trapped in the central minimum B mirror cell of each component drift within the minimum B magnetic field, where Mod.B surfaces are closed, so that are confined radially by the magnetic well. The ions going through the inner and outer mirror throats of each component, which are called passing ions, reach the plug region in the outermost end-mirror cells. Because the passing ions do not feel the minimum B magnetic field, these passing ions drift radially and are lost finally. However the passing ions have to travel a long distance from the plug to another plug, and then are expected to feel the smoothed out winding equi-potential surface and are expected to drift out very slowly. So the confinement time of the passing ions are expected to be long.

6. Summary

The new design of a tandem mirror has shown in this manuscript. The detailed calculation of ion and electron confinement times have to be carried out from now on. However, the essential idea of the design that the ions and electrons are tried to be confined by a magnetic well radially is very new. And the confinement time of plasma in the present tandem mirror is expected to be improved greatly.

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