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Heavy Impurity Ion Control in Modular Stellarators with Drift Optimized Configurations

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Introduction

The drift optimized configurations are realized in the advanced stellarators such as WENDELSTEIN 7-AS and WENDELSTEIN 7-X (Max-Planck Institut fur Plasmaphysik, EURATOM, Germany), National Compact Stellarator Experiment which is under construction in Princeton Plasma Physics Laboratory, USA, Compact Helical System Upgrade in the National Institute for Fusion Science, Japan, and others. In the drift optimized configurations the background ions and alpha-particles should be confined well. However not only background particles but impurity ions in the modern devices and cold alpha-particles in future reactors also would be well confined. It is necessary to find effective approaches to control impurity ions in the drift optimized configurations. During the last experiments on the WENDELSTEIN 7-AS stellarator with high density and low temperature discharges it was shown that impurity ions such as carbon and oxygen do not penetrate to the plasma core [1]. For the future reactor HELIAS impurity ions behaviour especially tungsten ions behaviour at the plasma edge is of a great interest. The effect of the external perturbations on the impurity ions was also observed on tokamak [2]. In present work the attempt to investigate impurity ions behaviour in stochastic layer at the edge of plasma was undertaken. Stochastic layer can take place at the periphery because of the some plasma instability or the secondary magnetic field resonances. As a result of such instabilities magnetic surfaces, which are regular in the absence of the perturbations, can lead to the stochastic ion trajectories under the set of perturbations [3]. Stochastic behavior of the heavy ion (tungsten) trajectories at the edge of plasma is demonstrated here for the HELIAS Reactor configuration. Such situation can take place if the external magnetic field perturbations are applied in the stationary way. This approach can be used in other drift-optimized systems. Another possibility to affect the impurity ions can be connected with the AC electric field.

Stochastic Magnetic Fields as the Barrier to Heavy Impurity Ions in Advanced Stellarators

Magnetic Field Model

The magnetic field is introduced in the following form

$$B_r = 0\,,\; B_\vartheta = B_0 \frac{r}{R}\iota\,(r^2)\,,\; B_\varphi = \frac{B_0}{1 - \dfrac{r}{R}\cos\vartheta + \varepsilon_M \cos\,(M\varphi)}\,. \qquad (1)$$

In such way the magnetic field corresponds to the main features of the toroidaly closed magnetic configuration. To find the resonance and resonance overlapping the additional magnetic field perturbation in the "wave"-form is added

$$\delta B_r = \alpha_{n\,m\,\omega} \sum_{n\,m\,\omega} \left(\frac{r}{a}\right)^{n-1} \sin(n\vartheta - m\varphi + \omega\, t)\,,$$

$$\delta B_\vartheta = \alpha_{n\,m\,\omega} \sum_{n\,m\,\omega} \left(\frac{r}{a}\right)^{n-1} \cos(n\vartheta - m\varphi + \omega\, t)\,, \qquad (2)$$

$$\delta B_\varphi = 0\,.$$

Here $\alpha_{n,m,\omega}$ is the perturbation field amplitude, n and m are the "wave" numbers, ω is the frequency of the perturbation field.

Particle Orbits

One of new approaches to control impurity ions for the drift-optimized configurations is the creation of the stochastic layer at the edge of plasma or some outside of it. Magnetic surfaces, which are regular in the absence of the perturbations, can lead to the stochastic ion trajectories under the set of perturbations [3]. Stochastic behavior of the heavy ion (tungsten) trajectories at the edge of plasma is demonstrated here for the HELIAS Reactor configuration (Fig.1). Here the following parameters of the particle are taken: ion charge number Z=30, energy of tungsten W=1 keV, $V_{\|}/V$=0.7. The parameters of two perturbations are the following: m=10, n=9, $\alpha = 2\cdot 10^{-6}$ and m=19, n=17, $\alpha = 5\cdot 10^{-5}$.Some particles can come from the external part of the layer into the internal part (Fig.2) and other particle come out from the internal part of the layer to the external part of the layer (Fig.3). Therefore in total there cannot be the transport of impurity ions inside the confinement volume. There are some experimental indications [1,2] on the possibility to stop the impurity ions at the edge of plasma.

Non- averaged test particle flux

The particle flux not averaged on the magnetic surface, namely $V_r f_1^*$, in the frame work of neoclassical approach can be written in the following form

$$V_r f_1^* = \left\{ (\upsilon_D)^2 \frac{\nu}{\left(\frac{\upsilon_\|}{R}\iota - \frac{\upsilon_E}{r}\right)^2 + \nu^2} + (-1)\left(\frac{\upsilon_\|}{B}\delta B_{r\, n_k\, m_k\, \omega_k}\right)^2 \frac{\nu}{\Omega^2_{n_k\, m_k\, \omega_k} + \nu^2} \right\} \frac{1}{2}\frac{\partial f_0}{\partial \psi_0}\nabla_r \psi_0, \quad (3)$$

where

$$v_D = \frac{\upsilon^2 + \upsilon_\|^2}{\omega_c}\frac{1}{R}, \quad \omega_c = \frac{ZeB_0}{Mc}, \quad \Omega_{n_k\, m_k\, ,\omega_k} = \omega_k - n_k\left(\frac{\upsilon_\|}{R}\iota - \frac{\upsilon_E}{r}\right) - m_k\left(\frac{\upsilon_\|}{R} + \frac{\upsilon_E}{R}\frac{r}{R}\iota\right). \quad (4)$$

Above the toroidal magnetic field and the magnetic perturbation corrections are taken into account. Here ω_k, n_k, m_k are the frequency and the "wave" numbers of the magnetic perturbation, υ is the total particle velocity, $\upsilon_\|$ is the velocity along the magnetic field, υ_E is the $[\mathbf{E}\times\mathbf{B}]$drift velocity ($\upsilon_E = c\frac{E_r}{B}$), ι is the rotational transform. Other denotations are well common. This expression indicates on the resonance conditions which is the subject of the further study. Stochastic properties of the magnetic field can be combined with other physics mechanisms such as drift island motion [4,5] and estafette of drift resonances [6] which also can be used to control the impurity ions.

Effect of AC electric field on the particle drift velocity.

It should be noticed that the parallel AC electric field could affect the drift velocity of the particles, which is connected with the gradients of the magnetic field [7]. As it can be seen from the guiding center equations the well known part of the drift velocity due to toroidal inhomogenuity

$$v_D = \frac{\upsilon^2 + \upsilon_\parallel^2}{\omega_c} \frac{1}{R} \tag{5}$$

should be added with the following term,

$$\frac{\tilde{E}_\varphi}{B_0} \varepsilon_t \frac{R}{Ma} \varepsilon_l \left(\frac{r}{a} \right)^l \sin(\omega_E t + \delta_E)\,, \tag{6}$$

where $\tilde{E}_\varphi$ is the amplitude of the externally applied parallel electric field (AC electric field), $\varepsilon_t \equiv \frac{a}{R}$ is the aspect ratio, $\varepsilon_l \left(\frac{r}{a} \right)^l$ is the helical inhomogenuity, ω_E and δ_E are the frequency and the phase of the AC electric field.

During the half of the period of AC electric field variation this term can decrease the velocity and increase it during the other half-period. These one and other closed possibilities are under the further study now.

Conclusions

1. Stochastic magnetic fields can be the barrier on the way of impurity ions into the center of plasma.
2. AC electric field, which can affect the drift velocity of the test particle, can be helpful for the control impurity ions at the edge of plasma.

Acknowledgments

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Figure Captions

Fig.1. Stochastic behavior of the tungsten trajectory

Fig.2. Transport of particle from the external part of stochastic layer into the internal part

Fig.3. Transport of particle from the internal part of stochastic layer into the external part

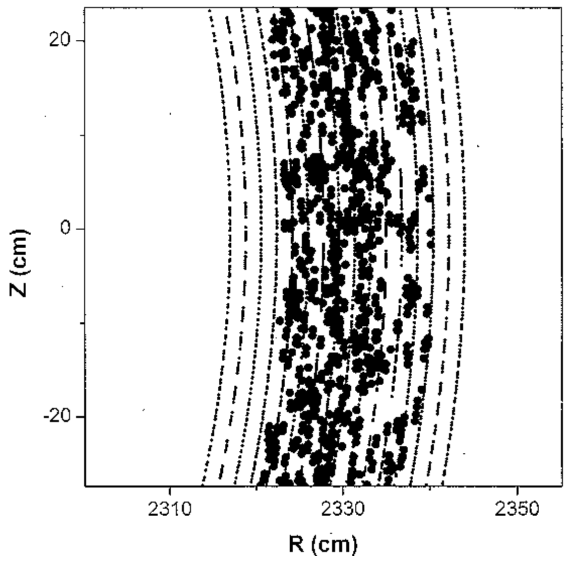

Fig.1

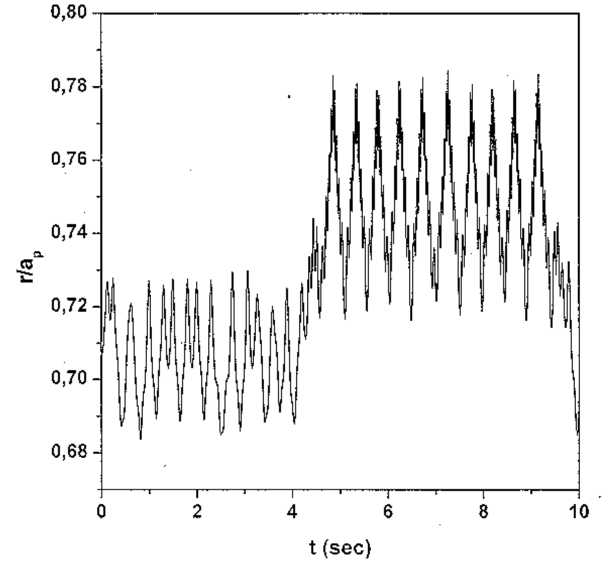

Fig.2

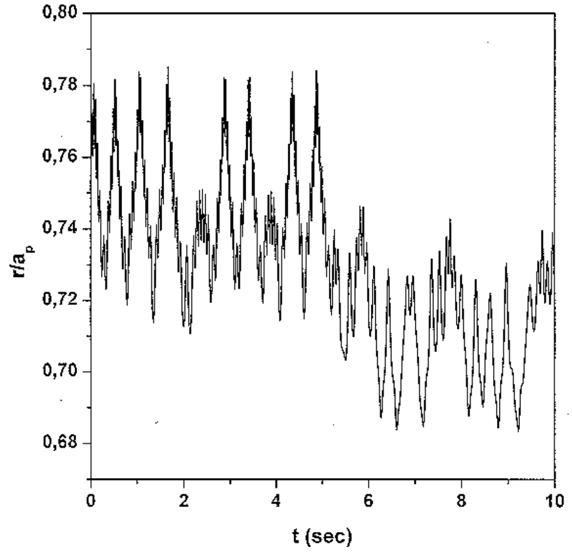

Fig.3