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The effect of magnetic field modification on heavy ion movement in advanced stellarators and helical devices

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Abstract

Two new physics mechanisms that can be used to shield and exhaust the impurity ions in the toroidal magnetic traps with the rotational transform from the external current coils are considered here. One of them is connected with the stochastic magnetic fields, which can be the barrier for the penetration of impurity ions from the outside in the confinement volume. This way is appropriate in advanced stellarator systems such as the Wendelstein 7 X and the Helias Reactor. Another approach is a possibility to use the process of transition of particles with the blocked trajectories into the helical trapped particles. The particles that should be removed from the center of the confinement volume can go away along the transit trajectories. Such mechanism can be used in the helical device with the noticeable fraction of the transit particles, particularly the large helical device.

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Keywords: Impurity ions; Stochastic magnetic fields; Loss cone losses; Helical device; Advanced stellarator

1. Stochastic magnetic fields as the barrier to heavy impurity ions in advanced stellarators

1.1. Magnetic field model

The magnetic field is introduced in the following form

$$B_r = 0, \quad B_\vartheta = B_0 \frac{r}{R}\iota(r^2),$$
$$B_\varphi = \frac{B_0}{1 - \frac{r}{R}\cos\vartheta + \varepsilon_M \cos(M\varphi)}, \tag{1.1}$$

where M and ε_M are the 'wave' number and the amplitude of the geometrical axis modulation.

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

$$\delta B_r = \sum_{n,m,\omega} \alpha_{n,m,\omega}\left(\frac{r}{a}\right)^{n-1} \sin(n\vartheta - m\varphi + \omega t),$$
$$\delta B_\vartheta = \sum_{n,m,\omega} \alpha_{n,m,\omega}\left(\frac{r}{a}\right)^{n-1} \cos(n\vartheta - m\varphi + \omega t), \tag{1.2}$$
$$\delta B_\varphi = 0.$$

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.

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1.2. Particle orbits

Advanced stellarators belong to the class of drift-optimized configurations. That means that the background ions and alpha particles in such configurations should be confined well. However not only background particles but also impurity ions in the modern devices and cold alpha particles in future reactors also would be confined well. It is necessary to develop new approaches to control impurity ions for the drift-optimized configurations. One of them is the creation of the stochastic layer at the edge of plasma. Magnetic surfaces, which are regular in the absence of the perturbations, can lead to the stochastic ion trajectories under the set of perturbations [1]. Stochastic behavior of the heavy ion (tungsten) trajectories at the edge of plasma is demonstrated here for the HELIAS reactor configuration (Fig. 1(a)). Here the following parameters of the particle are taken: ion charge number $Z = 30$, energy of tungsten $W = 1$ keV, $V_{\|}/V = 0.7$. These parameters are chosen for the demonstration here. The parameters of two perturbations are the following: $m = 10$, $n = 9$, $\alpha = 2 \times 10^{-6}$ and $m = 19$, $n = 17$, $\alpha = 5 \times 10^{-5}$. Some particles can come from the external part of the layer into the internal part (Fig. 1(b)) and other particles come out from the internal part of the layer to the external part of the layer (Fig. 1(c)). Therefore in total there cannot be transport of impurity ions inside the confinement volume.

During the time observation, namely 10 s, we cannot see the loss of the particle in the absence of the sink at the plasma edge. There are some experimental

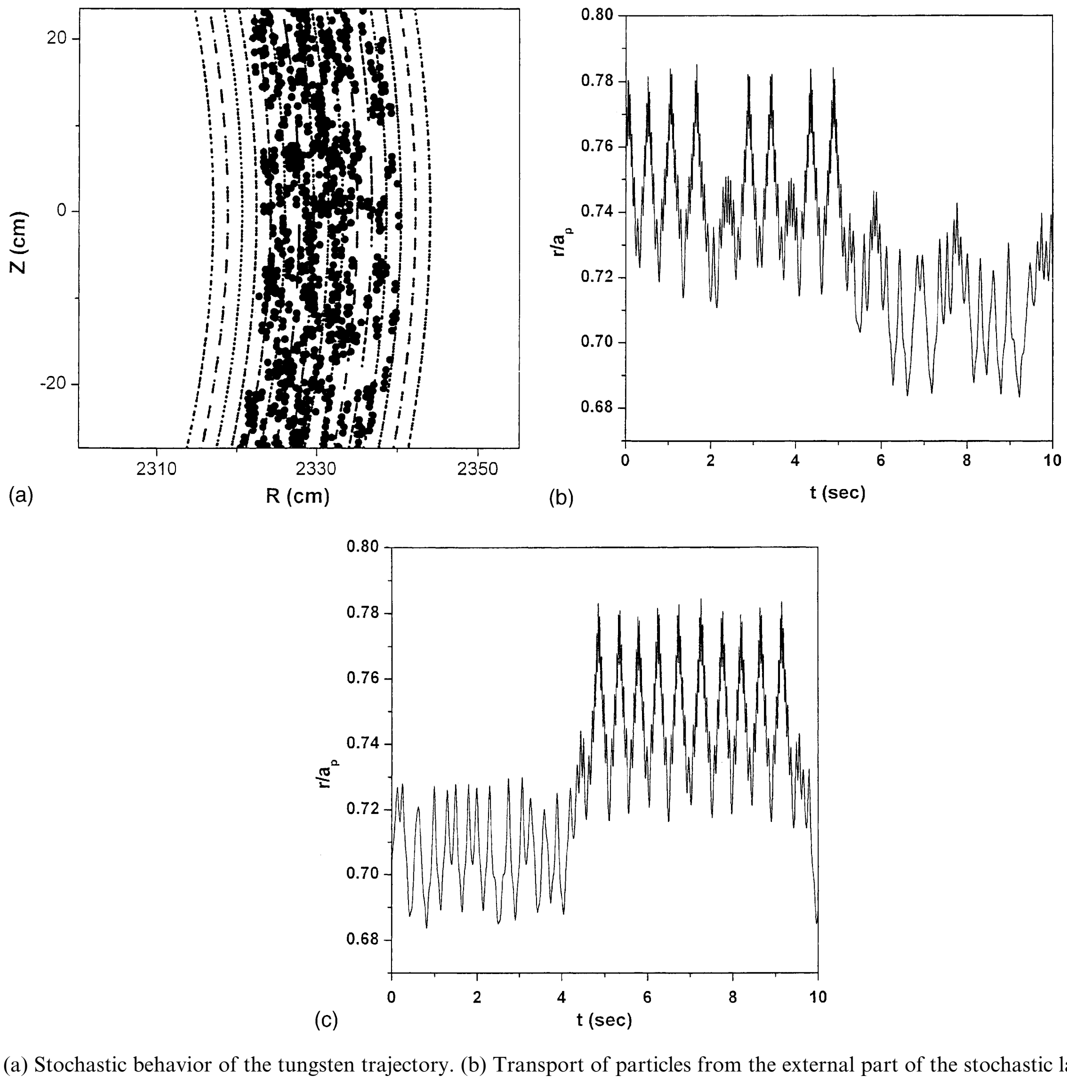

Fig. 1. (a) Stochastic behavior of the tungsten trajectory. (b) Transport of particles from the external part of the stochastic layer into the internal part. (c) Transport of particles from the internal part of the stochastic layer into the external part.

indications [2] of the possibility to stop the impurity ions at the edge of plasma. In numerical calculations single orbits are studied and collisions are not included. That is why the analytical expression is obtained to study the flux of the resonance particles.

1.3. Non-averaged resonance particle flux

In the frame work of the Galeev–Sagdeev neoclassical transport theory we obtain the part of the expression for the particle flux not averaged on the magnetic surface, namely $V_r f_1^*$ in the plateau regime with the toroidal magnetic field, the magnetic perturbation corrections and modularity of the magnetic field in the following form:

$$V_r f_1^* = \left\{ (v_{D,t})^2 \frac{\nu}{\left(\frac{v_\parallel}{R}\iota - \frac{v_E}{r}\right)^2 + \nu^2} + \left(\frac{v_\parallel}{B}\delta B_{n_k,m_k,\omega_k}\right)^2 \frac{\nu}{\Omega^2_{n_k,m_k,\omega_k} + \nu^2} + (v_{D,M})^2 \frac{\nu}{\left(\frac{v_\parallel}{R} + \frac{v_E}{R}\frac{r}{R}\iota\right)^2 + \nu^2} \right\} \times (-1)\frac{1}{2}\frac{\partial f_0}{\partial \psi_0}\nabla_r \psi_0, \quad (1.3)$$

where

$$v_{D,t} = \frac{v^2 + v_\parallel}{\omega_c}\frac{1}{R}, \quad \omega_c = \frac{ZeB_0}{Mc},$$
$$\Omega_{n_k,m_k,\omega_k} = \omega_k - n_k\left(\frac{v_\parallel}{R}\iota - \frac{v_E}{r}\right) - m_k\left(\frac{v_\parallel}{R} + \frac{v_E}{R}\frac{r}{R}\iota\right),$$
$$v_{D,M} = \frac{v^2 + v_\parallel}{\omega_c}\frac{r}{R}\iota\varepsilon_M M. \quad (1.4)$$

Here ω_k, n_k, m_k are the frequency and the 'wave' numbers of the magnetic perturbation, v is the total particle velocity, $v_\parallel$ is the velocity along the magnetic field, v_E is the drift velocity ($v_E = c(E_r/B)$), ι is the rotational transform, $\delta B_{n,m,\omega} \equiv \alpha_{n,m,\omega}(r/a)^{n-1}$. Other denotations are commonly known.

The resonance condition for the passing particle can give us the following expression

$$n_k = m_k \frac{1 + \frac{v_E}{v_\parallel}\frac{r}{R}\frac{m}{n}}{\frac{m}{n} - \frac{v_E}{v_\parallel}\frac{R}{r}} + \frac{1}{\frac{m}{n}\frac{v_\parallel}{R\omega_k} - \frac{v_E}{r\omega_k}}. \quad (1.5)$$

One can see that if the rational magnetic surface has the rotational transform $\iota = m/n$ the perturbation of the magnetic field with the 'wave' numbers m_k, n_k can disturb the particle orbit and lead to the selective stochasticity of the particle orbit. It means that magnetic surfaces are regular while passing particle orbits are stochastic.

2. Transition orbit use as the impurity ion control in a helical device

In the usual helical devices with flexible magnetic configurations such as the large helical device it is possible to use the different approaches, which can be developed on the basis of the regular (not destroyed) magnetic and drift surfaces. Such physics mechanisms as the drift island motion [3,4], estafette (relay race) of the drift resonances [5] can be used to control the impurity ions in modern devices and cold alpha particles in future helical reactors. In this paper we would like to emphasize the possible approach, which is connected with the transition of the particles from the passing and toroidally blocked into helically trapped [6]. Such particle can leave the confinement volume. This approach is especially effective in the configurations where the transition orbit phase space $(W, V_\parallel/V)$ is rather large. Here W and $V_\parallel/V$ are the energy and parallel velocity to total velocity ratio of the particles. The helical ripple loss cone is the key physics mechanism used here.

Potassium (K^+ ions) can be used in the experiment on the large helical device to simulate the behavior of the impurity ions and their removal from the device with the use of the transition processes.

2.1. Analytical description of the transit orbits

The particle starts its motion as a blocked one then crosses the transition curve and becomes the helically trapped one. The trajectory of the particle in the blocked state and then in the state of the helically trapped can be described with the equations $J_\parallel(r, \vartheta, V_\parallel/V) = \text{const}$, where $J_\parallel = \oint V_\parallel \, dl$ is the longitudinal adiabatic invariant of the particle in the corresponding state.

The starting points (with the coordinates r_0, ϑ_0) of particles, which start outside the last closed magnetic surface, cross the transition curve (at the point with coordinates r_t, ϑ_t) and should penetrate into the core of the confinement volume (to the point with the coordinates r_c, ϑ_c), can be found from the system of equations

$$J_{\parallel\,\text{hel.tr}}(r_0, \vartheta_0, V_\parallel/V) = J_{\parallel\,\text{hel.tr}}(r_t, \vartheta_t, V_\parallel/V), \quad (2.1)$$

$$J_{\parallel\,\text{blocked}}(r_t, \vartheta_t, V_\parallel/V) = J_{\parallel\,\text{blocked}}(r_c, \vartheta_c, V_\parallel/V), \quad (2.2)$$

$$2 = 1 + \frac{V^2 - \mu B_0 + \mu B_0 (r_t/R)\cos\vartheta_t}{\mu B_0 \varepsilon_{l,m}(A^2 + B^2)^{1/2}}, \quad (2.3)$$

where

$$A = \sum_n \frac{\varepsilon_{n,m}}{\varepsilon_{l,m}} \sin n\vartheta_t, \quad B = \sum_n \frac{\varepsilon_{n,m}}{\varepsilon_{l,m}} \cos n\vartheta_t. \quad (2.4)$$

Here $\varepsilon_{n,m}$ and $\varepsilon_{l,m}$ are the coefficients before the harmonics of the angular variables along the poloidal and toroidal directions: $\varepsilon_{l,m}$ is the amplitude of the main helical harmonic and $\varepsilon_{n,m}$ is the amplitude of the satellite harmonics.

The sets of parameters with the different signs and values of the coefficients $\varepsilon_{n,m}$ are responsible for the shift of the magnetic axis (outward or inward), the shape of the magnetic surfaces and the modulation of the magnetic field absolute value along the magnetic field line.

2.2. Penetration of potassium ions in the center of the confinement volume

In this paper we concentrated on the study of the K^+ ions in the inward shifted magnetic configuration. As the test particle the K^+ ion with the energy $W = 1$ keV is taken. One typical trajectory of the transit particle is shown in Fig. 2(a) (vertical cross-section) and (b) (horizontal cross-section). The starting points are found here with the rule of the orbit reversal. Under the starting point coordinates $r_0 = 60.537$ cm, $\vartheta_0 = 0.1251$ rad, $\varphi_0 = 1.035$ rad, $V_\parallel/V = -0.4$ the test ion starts as a helically trapped particle and then becomes a blocked one and stays as a blocked one during the time 6 ms. The period of the particle staying in the blocked state can be seen in Fig. 2(c). The 3-D trajectory of such a test ion is seen on Fig. 3. One can see the parts of the trajectory when the test ion is the helically trapped one and when it becomes the blocked (toroidally trapped) one.

The described effect – the penetration of the ions injected outside the last closed magnetic surface into the core of the confinement volume, can be reversed. It means that the impurity ions with transit orbits (cold

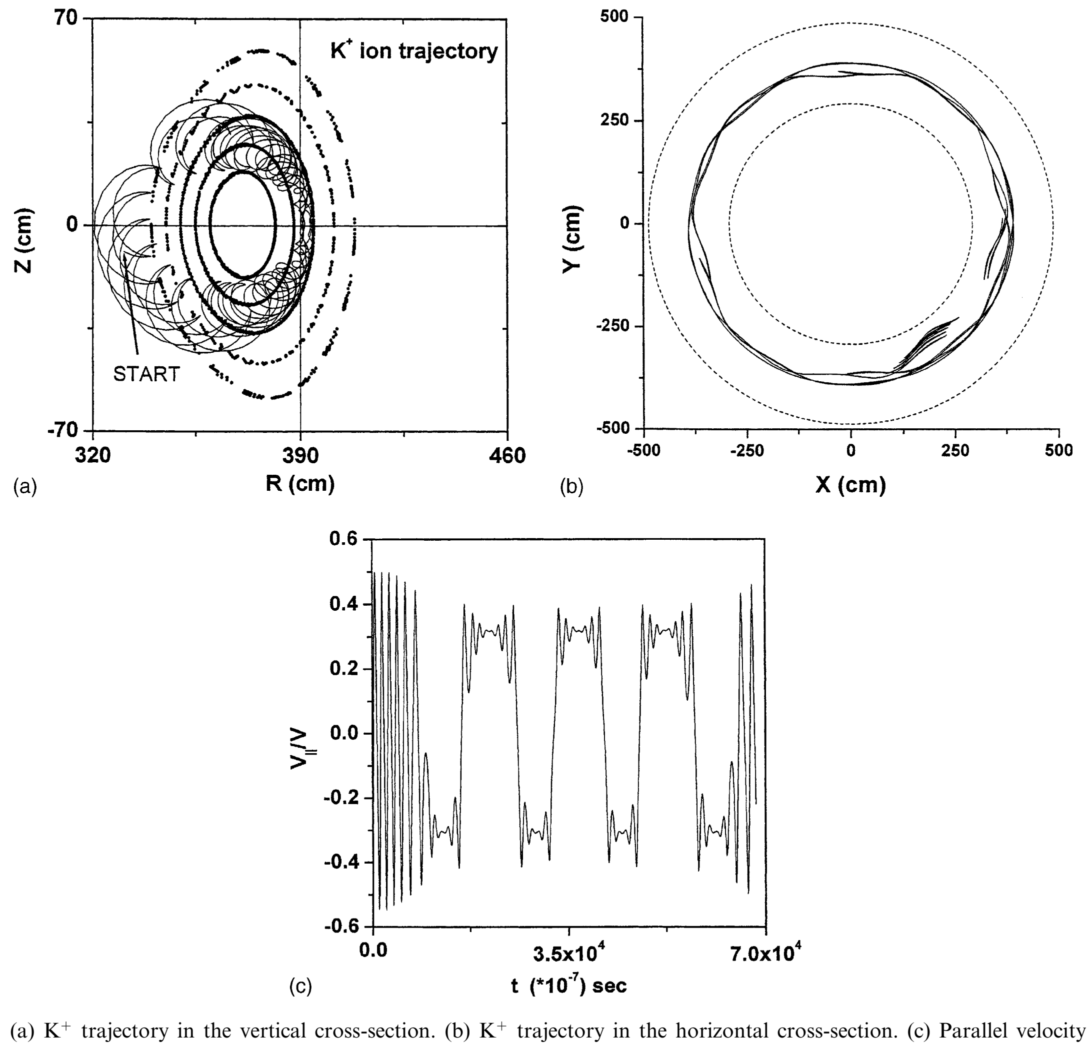

Fig. 2. (a) K^+ trajectory in the vertical cross-section. (b) K^+ trajectory in the horizontal cross-section. (c) Parallel velocity of the particle as a function of time.

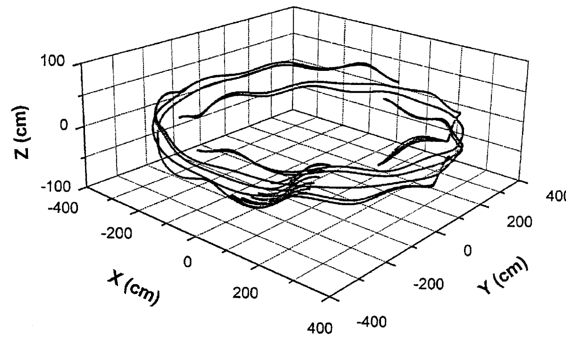

Fig. 3. K^+ 3-D trajectory in LHD.

alpha particles, particularly) can be removed from the core of the confinement volume to the periphery of the plasma.

3. Conclusions

1. The stochastic layer of the trajectories of impurity ions can prevent ions born near the wall from the entering into the core of plasma. This way is demonstrated numerically for the tungsten ion in a Helias configuration. There is obtained also the analytical relationship between the poloidal and toroidal mode numbers (n_k, m_k), frequency of the perturbation fields (ω_k), electric drift velocity to parallel velocity ratio ($\upsilon_E/\upsilon_{\parallel}$), rational magnetic surface parameters ($\iota = m/n$, R/r) and the selective stochasticity of the particle orbits.
2. Transit orbits of the heavy ions can be used for their escape from the center of helical devices with a noticeable fraction of transit particles. This way is demonstrated numerically for the potassium ions in large helical device.

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