THE INFLUENCE OF MAGNETIC ISLANDS ON THE IMPURITY ION MOTION IN THE DRIFT OPTIMIZED STELLARATOR

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The motion of the charged test particles ensemble of tungsten ions in the drift optimized stellarator Wendelstein 7-X with the chain of 5 magnetic islands is studied. The numerical code solves the guiding center equations written in the Hamiltonian form. To simulate the Coulomb scattering the Monte Carlo collision operator is used. The scattering of the particles due to the collisions and magnetic islands is shown. The question of the possibility to use the magnetic islands for the prevention of impurity penetration to the plasma is discussed.

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1. INTRODUCTION

The control of impurity ions plays the important role for the plasma confinement in the present-day toroidal fusion magnetic devices. Impurities come to the plasma from the walls and divertor plates and lead to the significant increase of the bremsstrahlung radiation losses. The most dangerous for the confinement are the impurities of heavy metals such as molybdenum and tungsten.

In this paper, the motion of the ensemble of tungsten impurity ions in the magnetic field of Wendelstein 7-X is studied. W7-X is the modular stellarator being constructed at Max-Planck-Institut für Plasmaphysik in Greifswald, Germany. The W7-X coil system consists of 50 modular and 20 planar non-circular coils combined in $M=5$ magnetic periods [1]. There are also 10 control coils used to control the magnetic island position. The coil system of W7-X is developed in such a way that the drift losses are minimized in this configuration. The main W7-X parameters are the following: the major plasma radius $R_0=5.5\ m$, minor plasma radius $a=0.52\ m$, the average magnetic field on the magnetic axis $B_0=2.5\ T$.

In our previous paper [2] it was shown how the magnetic islands influence on the impurity transport when the particles do not form the drift islands. In this paper, we concentrate our attention on a such collisionality regime when the particles form the drift island and study the influence of the magnetic islands on the particle dynamics.

2. MAGNETIC FIELD MODEL

For the analytical description and numerical calculations we use Boozer magnetic coordinates (ψ,θ,ϕ), where ψ is the label of the magnetic surfaces, θ and ϕ are the poloidal and toroidal angles, respectively. The strength of the equilibrium magnetic field, which has the nested magnetic surfaces is used in the following form:

$$B = B_0\,(1+\sum_{m,n} b_{mn}(r)\cdot\cos(m\theta - nM\phi))\,, \qquad (1)$$

where B_0 is the average magnetic field on the magnetic axis. The Fourier coefficients $b_{mn}(r)$ as the functions of the normalized radius r are presented in Fig.1 for the so-called vacuum standard configuration of W7-X. For the simplicity we consider the model magnetic field where only the diamagnetic $b_{00}(r)$, mirror $b_{01}(r)$, toroidal $b_{10}(r)$ and helical $b_{11}(r)$ harmonics are non-zero. For the different magnetic configurations of W7-X these harmonics are much larger than the rest of the harmonics [1]. In axisymmetric configurations the toroidal harmonic $b_{10}(r)$ is the leading and it provides the main contribution to the Shafranov shift of the magnetic surfaces. In W7-X it is significantly reduced compared to the geometrical inverse aspect ratio. The mirror harmonic $b_{01}(r)$ characterizes the ripple of the magnetic field strength on the magnetic axis. It can be used for the suppression of the bootstrap current in finite beta plasmas to improve the confinement [3]. It should be noted that the sign of this harmonic is opposite to the sign of the helical and toroidal harmonics. The helical $b_{11}(r)$ harmonic leads to the existence of the helically trapped particles and *1/ν* diffusion regime in a long mean free path limit.

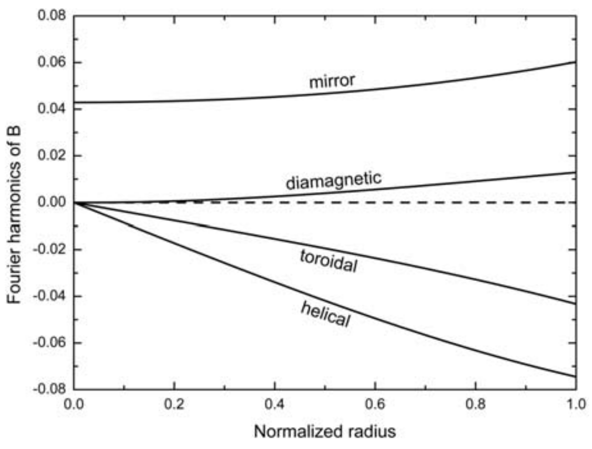

Fig.1. The Fourier harmonics of B for the standard configuration of W7-X

The magnetic islands are modeled by adding to the equilibrium magnetic field the perturbation in the following form [4]:

$$\delta\vec{B} = \nabla\times(\alpha\vec{B}_0)\,, \qquad (2)$$

where the function α, which has the unit of the length, presents a structure of the destroyed magnetic field. The perturbation function α is chosen in the form

$$\alpha = \alpha_0 r^m \sin(n\phi - m\theta) . \quad (3)$$

The total magnetic field can be presented as the sum of the equilibrium magnetic field and the perturbation $\delta\vec{B}$

$$\vec{B} = \vec{B}_0 + \delta\vec{B} . \quad (4)$$

For the W7-X configuration (with $M=5$ magnetic periods along the torus) the perturbation with the wave numbers $n=5$, $m=5$ was studied. This perturbation splits the rational magnetic surface $(r_{res} = 0.95)$, where the rotational transform is $\iota = 1$, into the chain of 5 magnetic islands (Fig.2). For the case of consideration the radial islands width was $\Delta \approx 4.9\,cm$.

We should note that the form of magnetic surfaces in W7-X stellarator in real geometry changes from the bean to the triangle depending on the toroidal angle ϕ. In Fig. 2 the magnetic surfaces are circular because we operate in Boozer magnetic coordinates where the magnetic lines are straight in (θ, ϕ) plane.

3. GUIDING CENTER EQUATIONS

To study the particle dynamics in the complicated stellarator magnetic field the guiding center equations written in the Hamiltonian form [4,5]:

$$\begin{cases} \dot{\psi} = (g\dot{P}_\theta - I\dot{P}_\phi)/\gamma, \\ \dot{\theta} = [(\mu + \rho_{||}^2 B)\frac{\partial B}{\partial \psi} g + \rho_{||} B^2(\iota - \rho_c g') - \\ \quad -\rho_{||} B^2 \frac{\partial \alpha}{\partial \psi} g]/\gamma, \\ \dot{\phi} = [-(\mu + \rho_{||}^2 B)\frac{\partial B}{\partial \psi} I + \rho_{||} B^2 (1 + \rho_c I') + \\ \quad +\rho_{||} B^2 \frac{\partial \alpha}{\partial \psi} I]/\gamma, \\ \dot{\rho_{||}} = [(1 + \rho_c I')\dot{P}_\phi + (\iota - \rho_c g')\dot{P}_\theta]/\gamma - \\ \quad -(\frac{\partial \alpha}{\partial \psi}\dot{\psi} + \frac{\partial \alpha}{\partial \theta}\dot{\theta} + \frac{\partial \alpha}{\partial \phi}\dot{\phi}), \\ \dot{P}_\theta = -(\mu + \rho_{||}^2 B)\frac{\partial B}{\partial \theta} + \rho_{||} B^2 \frac{\partial \alpha}{\partial \theta}, \\ \dot{P}_\phi = -(\mu + \rho_{||}^2 B)\frac{\partial B}{\partial \phi} + \rho_{||} B^2 \frac{\partial \alpha}{\partial \phi}, \end{cases} \quad (5)$$

are solved numerically using the Runge-Kutta method. Here, $\gamma = g + \iota I + \rho_c (g I' - I g')$ and $\rho_c = \rho_{||} + \alpha$. The system of equations (5) is written in the normalized form. All lengths are normalized to the major plasma radius R_0, the time is given in the units of $1/\omega_0$, where $\omega_0 = \frac{ZeB_0}{mc}$ is the particle gyrofrequency on the axis, the energy is normalized to $m\omega_0^2 R_0^2$, and the magnetic field strength is normalized to its average value on the magnetic axis B_0. The functions I and g are proportional to the toroidal and poloidal currents inside and outside the flux surface, respectively. The rotational transform profile $\iota(r)$ is taken in the form presented in Fig.3.

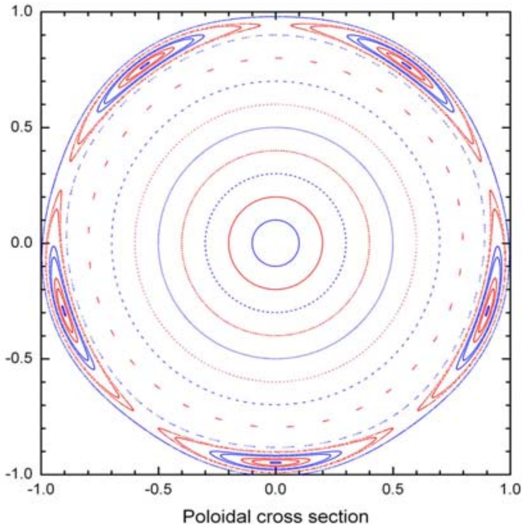

Fig.2. Poicaré plot of magnetic surfaces for $\phi = 0$

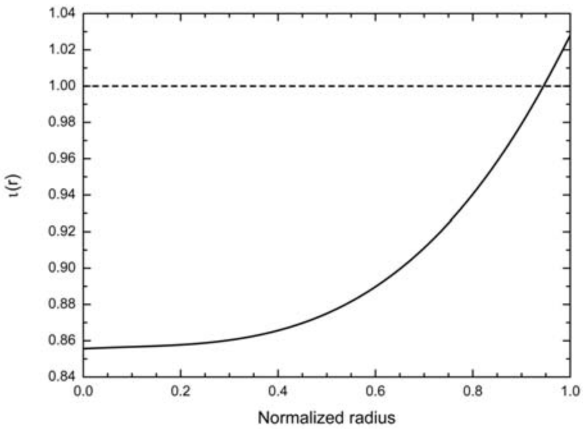

Fig.3. The profile of the rotational transform $\iota(r)$

4. COLLISIONAL OPERATOR

To model a collisional kick for a test particle in the pitch angle space, the discrete collision operator is applied after each integration time step. The Lorentz collision operator has the form [6]:

$$\lambda(t_n) = \lambda(t_{n-1})(1 - \nu_d\, \Delta t) \pm \sqrt{(1 - \lambda^2(t_{n-1})\nu_d\, \Delta t}, \quad (6)$$

where Δt should satisfy the condition $\nu_d \Delta t << 1$. The symbol "$\pm$" indicates that the sign should be chosen randomly, but with the equal probabilities for plus and minus.

The deflection can be calculated through the plasma parameters as [6,7]:

$$\nu_d^{\alpha/\beta} = \frac{4\pi\, e_\alpha^2 e_\beta^2 n_\beta \Lambda_{\alpha\beta}}{m_\alpha^2 \upsilon_\alpha^3} (\Phi(x^{\alpha/\beta}) - \Psi(x^{\alpha/\beta})) \quad (7)$$

Here e_α, m_α, and υ_α are the charge, mass, and the velocity of a test particle, e_β and n_β are the charge and the density of background particles (ions and electrons), $\Lambda_{\alpha\beta}$ is the Coulomb logarithm, and $x^{\alpha/\beta} = \upsilon^\alpha \Big/ \sqrt{\frac{2T_\beta}{m_\beta}}$ is the ratio of the test particle velocity to thermal velocity of the background particles.

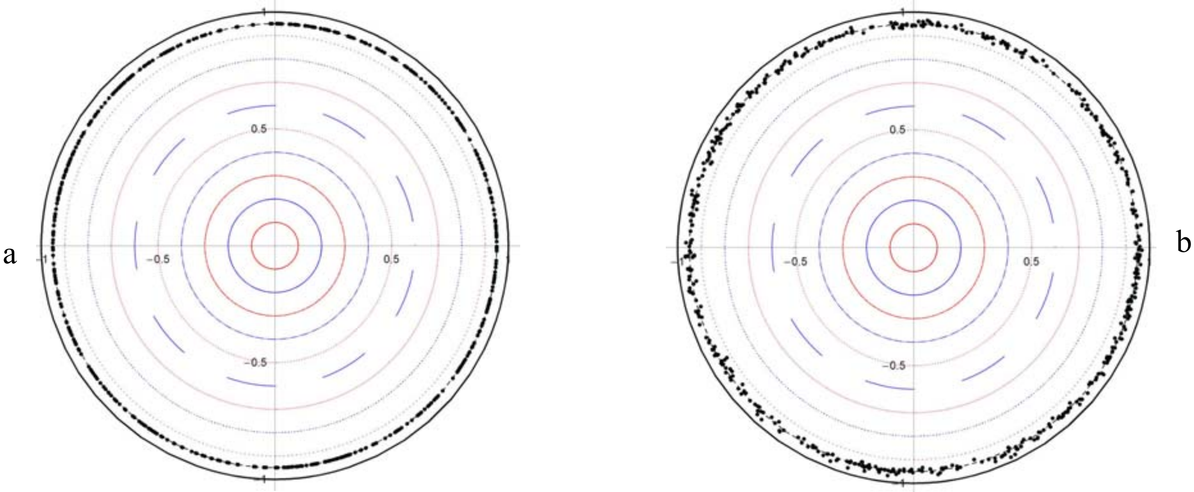

Fig.4. The scattering of the ensemble of 500 impurity ions for the case without magnetic islands (in the poloidal cross-section). (a) The initial positions of test ions; (b) Particle positions after 5 collision times

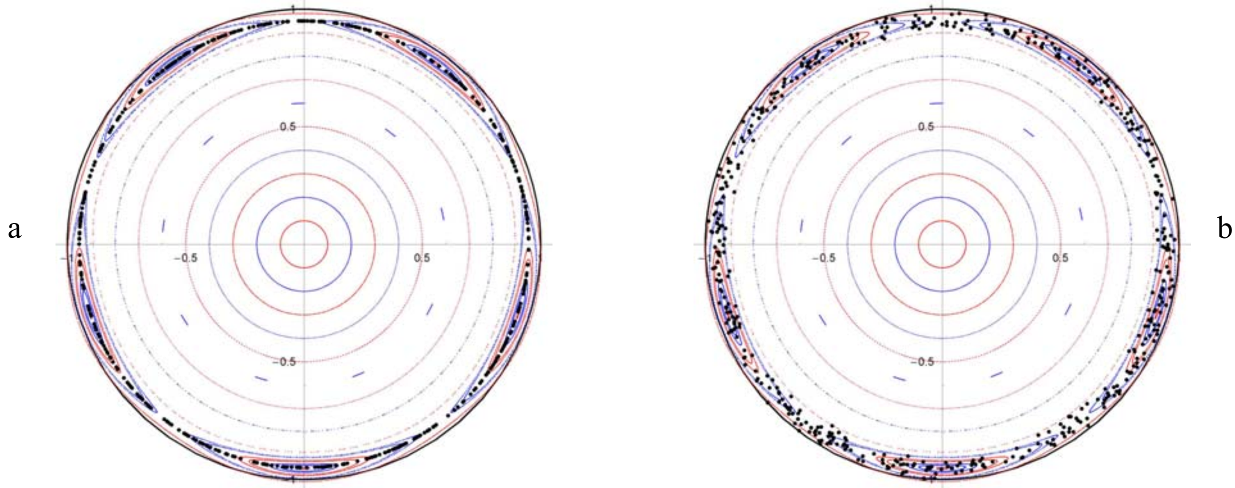

Fig.5. The scattering of the ensemble of 500 impurity ions in case of existence of the chain of 5 magnetic islands (in the poloidal cross-section). (a) The initial positions of test ions; (b) Particle positions after 5 collision times

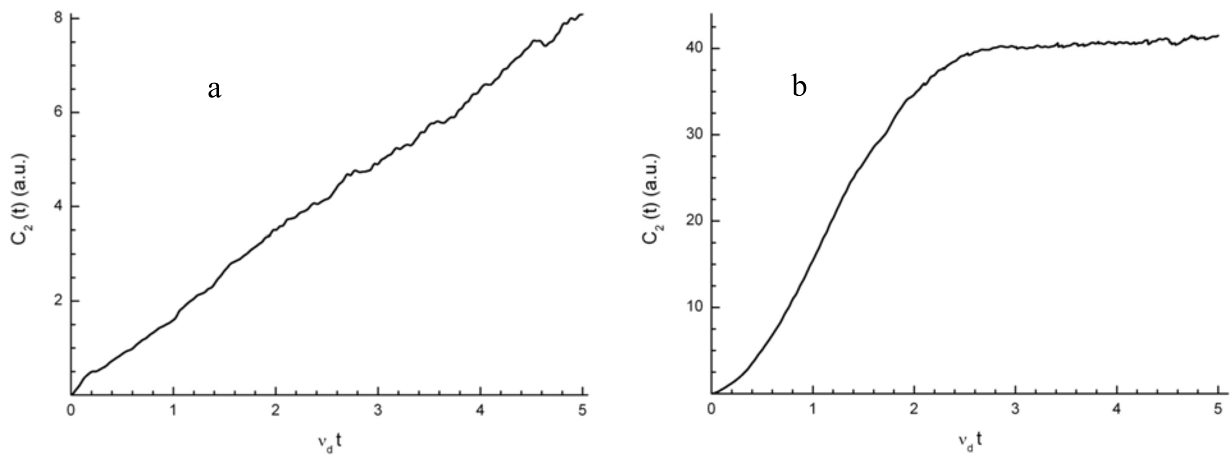

Fig.6. The temporal dependence of the mean-square displacement $C_2(t)$. (a) The configuration without magnetic islands; (b) The configuration with the chain of 5 magnetic islands

The functions Φ(x) and Ψ(x) are given by

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2)\, dt, \qquad (8)$$

$$\Psi(x) = (\Phi(x) - x\Phi'(x)) / 2x^2. \qquad (9)$$

In this paper, we study the collisionality regime when the normalized deflection frequency is $\tilde{\nu}_d = 1.0 \times 10^{-5}$.

5. PARTICLE SCATTERING

The particles of the monoenergetic ensemble of $N = 1000$ impurity ions with the energy $E = 3\,keV$ with randomly distributed initial pitch angles starts their motion from the same initial radial coordinate $r_0 = 0.95$, where $\iota = 1$. The initial poloidal and toroidal angles of particles are distributed randomly but uniformly. We study the motion of tungsten impurity ions with the atomic mass number A=184 and the charge state Z=30. Each particle evolves independently of others according to equations (5) and its initial conditions. The pitch angle of a particle is changed at each time step using the Monte Carlo collision operator (6).

As the measure of statistical properties of the ensemble, the mean square displacement is calculated: $C_2 = <(\delta r(t) - <\delta r(t)>)^2>$, where $\delta r(t) = r(t) - r_0$ is the particle radial displacement. Brackets mean the ensemble average: $<X> = \frac{1}{N}\sum_{i=1}^{N} X_i$, where N is the number of particles of the ensemble. The number of particles of the ensemble was chosen to satisfy 2 contradictory conditions: the number of particles should be enough large to obtain good statistics but not very large in order to preserve the CPU time.

Fig.4 presents the scattering of the ensemble of 500 impurity ions for the case without magnetic islands. The particles do not strongly deviate from the initial magnetic surface after 5 collision times $t_E = 5/\nu_d$ in the radial direction. Fig.6,a shows the linear increase in time of $C_2(t)$ for this case. It means that we have the normal diffusive process with the diffusion coefficient defined as $D(t) = \frac{1}{2}\frac{dC_2(t)}{dt}$ [6].

Fig.5 presents the scattering of the similar ensemble but for the case when the chain of 5 magnetic islands exists in the plasma. In the considered collisionality regime the particles form the drift islands. Thus, particles are allowed to have large radial deviations. As it is shown in Fig.5,b, the particles nearly uniformly fill the islands region after 5 collision times. In this case the mean-square displacement $C_2(t)$ saturates to the constant value, as it is shown in Fig.6,b.

The chain of the magnetic islands acts as the trap for the particles. The particles move just inside and are accumulated in the region of islands. The control of particle motion using the magnetic islands can be used to prevent the penetration of the impurities to the central regions of the plasma from the walls.

SUMMARY

In this paper, the impurity ion motion is studied for the standard configuration of W7-X stellarator when the chain of 5 magnetic islands exists at the plasma periphery. The mean square displacement of the ensemble of impurity ions is calculated for the case without magnetic islands and with them. It is shown that the magnetic islands can prevent the penetration of impurity ions into the centre of the plasma and lead to the change of the regime of the particle transport.

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ВЛИЯНИЕ МАГНИТНЫХ ОСТРОВОВ НА ДВИЖЕНИЕ ПРИМЕСНЫХ ИОНОВ В ДРЕЙФОВО-ОПТИМИЗИРОВАННОМ СТЕЛЛАРАТОРЕ

Ж.С. Кононенко, А.А. Шишкин

Изучено движение ансамбля заряженных тестовых частиц ионов вольфрама в дрейфово-оптимизированном стеллараторе Вендельштайн 7-Х с цепочкой из пяти магнитных островов. Уравнения ведущего центра, записанные в гамильтоновской форме, решаются численно. Для моделирования кулоновского рассеяния используется дискретный оператор Монте-Карло. Показано рассеяние частиц в полоидальном сечении под воздействием столкновений и магнитных островов. Обсуждается вопрос о возможности использования магнитных островов для предотвращения проникновения примесей в плазму.

ВПЛИВ МАГНІТНИХ ОСТРОВІВ НА РУХ ІОНІВ ДОМІШКИ У ДРЕЙФОВО-ОПТИМІЗОВАНОМУ СТЕЛАРАТОРІ

Ж.С. Кононенко, О.О. Шишкін

Вивчено рух ансамблю заряджених частинок іонів вольфраму у дрейфово-оптимізованому стелараторі Вендельштайн 7-Х з ланцюгом з п’яти магнітних островів. Рівняння ведучого центру, що записані у гамільтоновій формі, розв’язуються чисельно. Для моделювання кулонівського розсіяння використовується дискретний оператор Монте-Карло. Показано розсіяння частинок в полоїдальному перерізі під впливом зіткнень та магнітних островів. Обговорюється питання про можливість використання островів для запобігання проникання домішок у плазму.