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ESTAFETTE OF DRIFT RESONANCES IN TOKAMAK CONFIGURATION WITH REVERSED-SHEAR

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Induced particle transport by applying perturbations of the magnetic field with low poloidal "wave" numbers is studied by means of computer simulations. Reversed-shear operation regime for tokamaks is considered. The dependence of drift rotational angle transform profile on particle energy is calculated. The range of particle energies corresponding to reversed shear profile is defined. The removal of helium test particle from the plasma core to the periphery is demonstrated.

KEY WORDS: particle motion control, estafette of drift resonances, reversed shear tokamak, guiding center equations, computer simulation.

The development of fusion technology requires methods of particle motion control. They are necessary for different tasks in modern experimental devices. The conversion of trapped particles into passing ones with the goal to reduce neoclassical transport, the removal of the impurities, particle injection are the most important among them. Fusion reactor also needs an effective method of helium ash removal.

ESTAFETTE OF DRIFT RESONANCES

One of the methods to control particle motion in toroidal magnetic traps with rotational transform is the usage of drift islands. It is well known, that mode-*m* magnetic islands can appear at the magnetic surface with rotational transform angle $\iota = n/m$, when a magnetic perturbation with "wave" numbers *m* and *n* is present. The drift islands are shifted with respect to magnetic islands. The magnitude of this shift depends on the energy of the particle W and both the magnitude and the sign of pitch velocity $\mathrm{v}_{\|}/\mathrm{v}$. The position of drift islands depends on the poloidal magnetic field. The width of the drift islands depends on the amplitude of the perturbation and magnetic shear.

There are several methods to control particle motion proposed up to date. Fruitful idea was proposed by Mynick [1]. The method utilizes single-harmonic, 'rotating' magnetic perturbation with low poloidal wave number *n*:

$$\tilde{b} \equiv \delta B_r / B_0 = b_{mn}(r)\sin(n\theta - m\varphi - \omega t)\ . \qquad (1)$$

Here b_{mn} is amplitude of the perturbation, θ is poloidal angle, φ is toroidal angle, *n* and *m* are poloidal and toroidal "wave" numbers respectively. The perturbation induces a chain of islands with radial position r_{res} dependent on frequency ω. The resonance condition takes the following form

$$\iota^*(r_{res}) - \frac{n}{m} - \frac{\omega R}{m\bar{\mathrm{v}}_{\|}} = 0\ . \qquad (2)$$

Here ι^* is the drift rotational angle transform, *R* is the major radius, $\bar{\mathrm{v}}_{\|}$ is the mean parallel velocity. If ω is varied in time slowly enough, a particle starting inside an island will move adiabatically with that island. The method was studied experimentally at Compact Auburn Torsatron (CAT) [2]. It was shown that frequency sweeping resulted in radial motion of the test particles.

Another idea is 'drift island motion concept'. The 'drift island motion concept' represents the idea of keeping the drift rotational transform of passing particle of a certain energy and pitch velocity in resonance with the magnetic perturbation field during the motion of the particle, and to control the position of the drift island through the cross section in time [3].

Foregoing methods deal with non-stochastic motion of the particles. At the same time methods utilizing stochastic motion are developed also [4,5]. A.A. Shishkin in his work [6] advanced the concept of the estafette of drift resonances.

The main idea of the estafette of drift resonances (or the relay-race of drift resonances) is overlapping of the adjacent resonance structures that leads to stochasticity of particle trajectories. By consecutive overlapping of the drift islands it is possible to remove a particle from the center of the confinement volume to the periphery of the plasma.

This method was applied to particles confined with a stellarator type field with the drift rotational angle growing monotonically from the center to the periphery [6]. In this paper the estafette of drift resonances is used for helium ash removal in tokamaks with a reversed shear. Reversed-shear or negative-central-shear operation is characterized by a region where the magnetic shear

$$s = \frac{r}{q}\frac{dq}{dr} \tag{3}$$

is negative in the core region. Here q is the safety factor and r is the minor radius. Reversed-shear regime is promising good confinement with a large fraction of the bootstrap current [7,8]. Reversed-shear profile provides pairs of resonances located on both sides of $q_{\min}$. Inner and outer regions have the same set of resonances. That may cause a countermotion of the particles.

SIMULATION MODEL

Particle motion is described by guiding-center equations. When the external electric field is equal to zero ($\mathbf{E}=0$) and the magnetic field does not depend on time these equations can be written as follows

$$\frac{d\mathbf{R}}{dt} = \mathrm{v}_{\|}\frac{\mathbf{B}}{B} + \frac{mc\left(2\mathrm{v}_{\|}^{2}+\mathrm{v}_{\perp}^{2}\right)}{2eB^{3}}\left[\mathbf{B},\nabla B\right], \tag{4}$$

$$\frac{dW}{dt} = 0, \tag{5}$$

$$\frac{d\mu}{dt} = 0. \tag{6}$$

Equations (5)-(6) can be integrated:

$$W = \frac{m}{2}\left(\mathrm{v}_{\|}^{2}+\mathrm{v}_{\perp}^{2}\right) = const, \tag{7}$$

$$\mu = \frac{m\mathrm{v}_{\perp}^{2}}{2B} = const. \tag{8}$$

From equations (7) and (8) perpendicular and parallel velocities are expressed in terms of initial conditions

$$\mathrm{v}_{\perp} = \mathrm{v}_{0\perp}\sqrt{\frac{B}{B_{init}}}, \tag{9}$$

$$\mathrm{v}_{\|} = \sqrt{\mathrm{v}_{0}^{2} - \mathrm{v}_{0\perp}^{2}\frac{B}{B_{init}}}, \tag{10}$$

where initial velocity v_0 and initial perpendicular velocity $\mathrm{v}_{0\perp}$ are defined by pitch velocity $\mathrm{v}_{\|}/\mathrm{v}$, energy W and magnetic field B_{init} at the starting point.

For simplicity we consider concentric circular magnetic surfaces describing the equilibrium magnetic field

$$\mathbf{B}_0 = \frac{B_0}{1+(r/R)\cos\theta}\left(0, \frac{r}{R}\iota, 1\right), \tag{11}$$

where B_0 is the magnetic field at the axis, r is the minor and R is the major radii, ι is the rotational transform angle, θ is the poloidal angle. For the simulation the safety factor $q = 1/\iota$ profile is taken to vary quadratically with the minor radius reaching the minimum $q_{\min} = 1.85$ at $r/a = 0.7$. The value of $q_{\min}$ was chosen in order to get n=2, m=1 resonance in the region with low magnetic shear. Thus the width of the island would be large.

$$q\left(\frac{r}{a}\right) = 1.85 + 25.56\left(\frac{r}{a} - 0.7\right)^{2}. \tag{12}$$

Under the perturbation

$$\mathbf{B}_1 = b_{n,m}\left(\frac{r}{a}\right)^{n-1}\left(\sin\varsigma, \cos\varsigma, 0\right), \tag{13}$$

where $\varsigma = n\theta - m\phi + \psi_{n,m}$, the rational magnetic surface with the radius $r_{n,m}$ is split and the chain of m islands appears, where n gives the periodicity along the torus.

SIMULATION RESULTS

Drift rotational angle transform depends on the energy of the particle. Reversed-shear profile is realized only in a certain range of particle energies. It was found that the shear in the central part is increasing and it becomes positive from negative with the growth of energy. Drift rotational transform profiles for different values of particle energies are shown in Fig.1.

Obtained data was used for choosing particle energy in further simulations. In order to involve lower *n* resonances into the estafette the strongly reversed-shear profile was chosen, corresponding energy value is 15 keV. Drift rotational transform profile for this energy is shown in Fig.2. Drift rotational angle transform profile makes possible the usage of wide set of resonances. In this work we consider only two resonances 1/3 and 1/2.

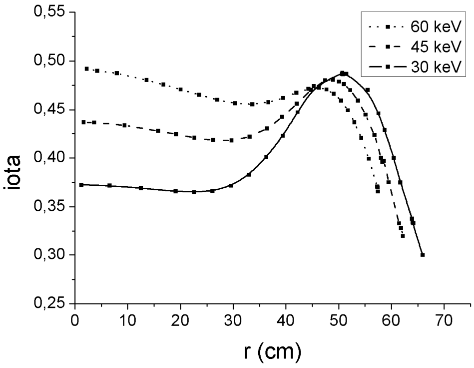

Fig.1. Drift rotational transform profiles for different values of particle energies.

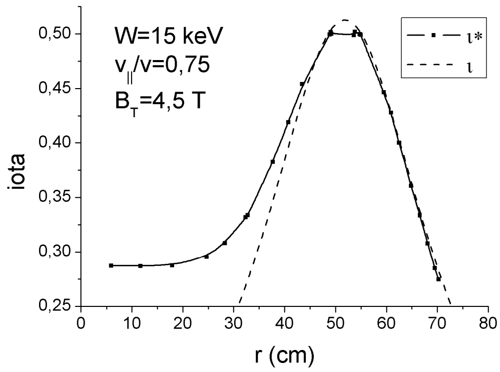

Fig.2. Drift (solid line) and magnetic (dotted line) rotational angle transform.

Under the set of perturbations $m=3,\ n=1,\ b_{3,1}=2\ 10^{-3}\,T,\ \psi_{3,1}=\pi/2$ and $m=2,\ n=1,\ b_{2,1}=3\ 10^{-3}\,T,$ $\psi_{2,1}=\pi/2$ resonant surfaces are split into a chain of islands (Fig.3). Let us consider the mechanism of the estafette of drift resonances. The perturbation of the magnetic field with the poloidal "wave" number *n* and the toroidal "wave" number *m* splits the resonant drift surface with the drift rotational angle transform $\iota^*=n/m$ into a chain of drift islands. If the amplitude of the perturbation is not large, the trajectories of the particles are not stochastic. We get the chains of drift islands isolated from each other the by drift surfaces, which may be deformed, but still are existing (Fig.4). With the growth of the perturbation amplitude the drift surfaces between the chains of islands are destroying one after another. When the amplitude is large enough, the last drift surface is destroyed and an ergodic region is formed (Fig.5). A particle can travel stochastically through the ergodic layer from one resonance to another. That is called the overlapping of the drift resonances (Fig.6). By consecutive switching perturbations on and off at certain moments of time we manipulate the overlapping of the drift resonances. The particle starts moving from the chain of islands at the plasma core consecutively passes to the next chain of islands at the larger radius. Thus passing from one resonance to another it moves from the plasma core to the edge. This process is similar to the relay-race (estafette), where particle is a stick and drift resonances are runners.

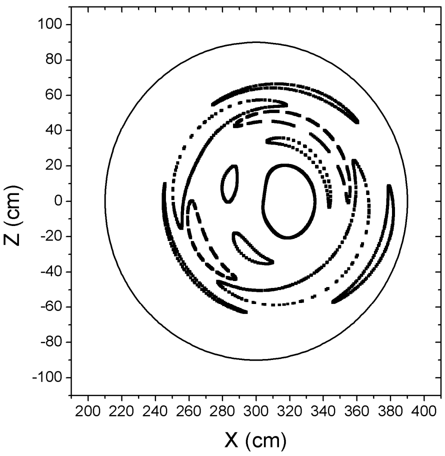

Fig.3. Drift islands.

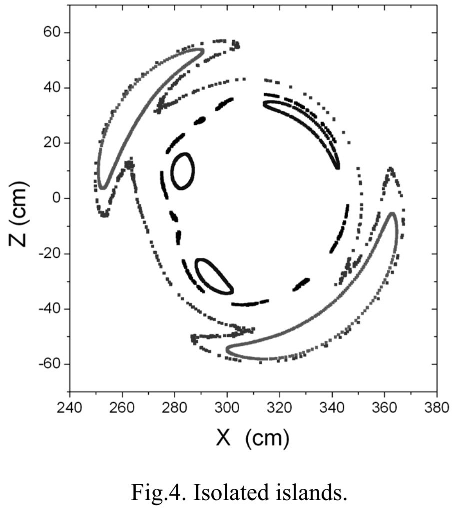

Fig.4. Isolated islands.

The estafette begins at initial time taken as $t=0$ at $r_{start}=43\,cm,\ \theta_{start}=0,\ \phi_{start}=0$. This point is lying on the resonant surface with drift rotational transform angle $\iota^*=1/3$. Initial perturbation amplitude is chosen as follows: $b_{3,1}=4\cdot10^{-3}\ T$. When $t=224\ \mu s$ perturbation $b_{2,1}=6\cdot10^{-3}\ T$ is switching on, causing the growth of radial deviation of the particle. At $t=543\ \mu s$ after the beginning of the observation, radial deviation reaches a maximum and the perturbation $b_{2,1}=1.8\cdot10^{-2}\ T$ is amplified. After that the particle is moving through the resonant structure with $\iota^*=1/2$. Then at $t=2490\ \mu s$ the perturbation $b_{2,1} = 6\cdot10^{-3}$ T is reduced and $b_{3,1} = 1.2\cdot10^{-2}$ T is amplified. When the radial deviation reaches a maximum at $t = 5017\,\mu s$, all perturbations are switching off leaving test helium particle at the periphery. Thus the test particle was removed from the plasma core to the edge (Fig.7).

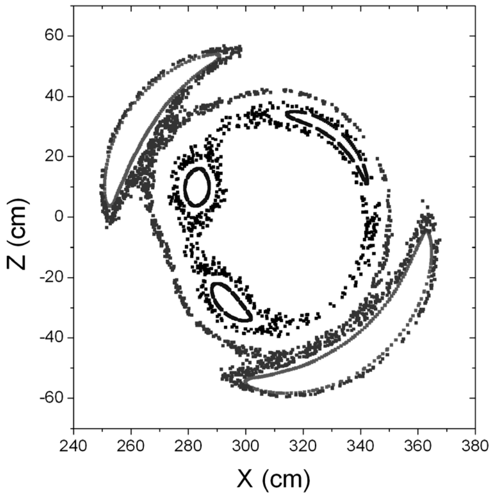

Fig.5. Stochastization of the trajectories

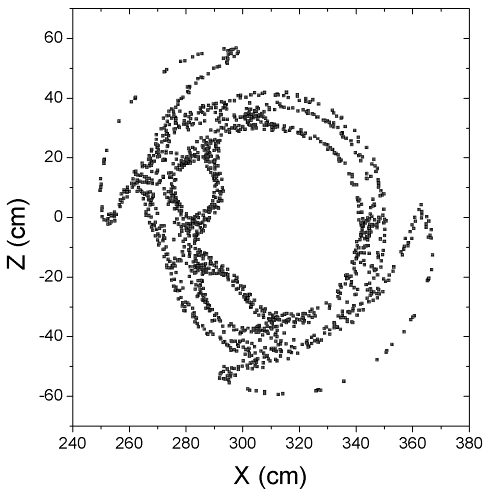

Fig.6. Overlapping of the resonances

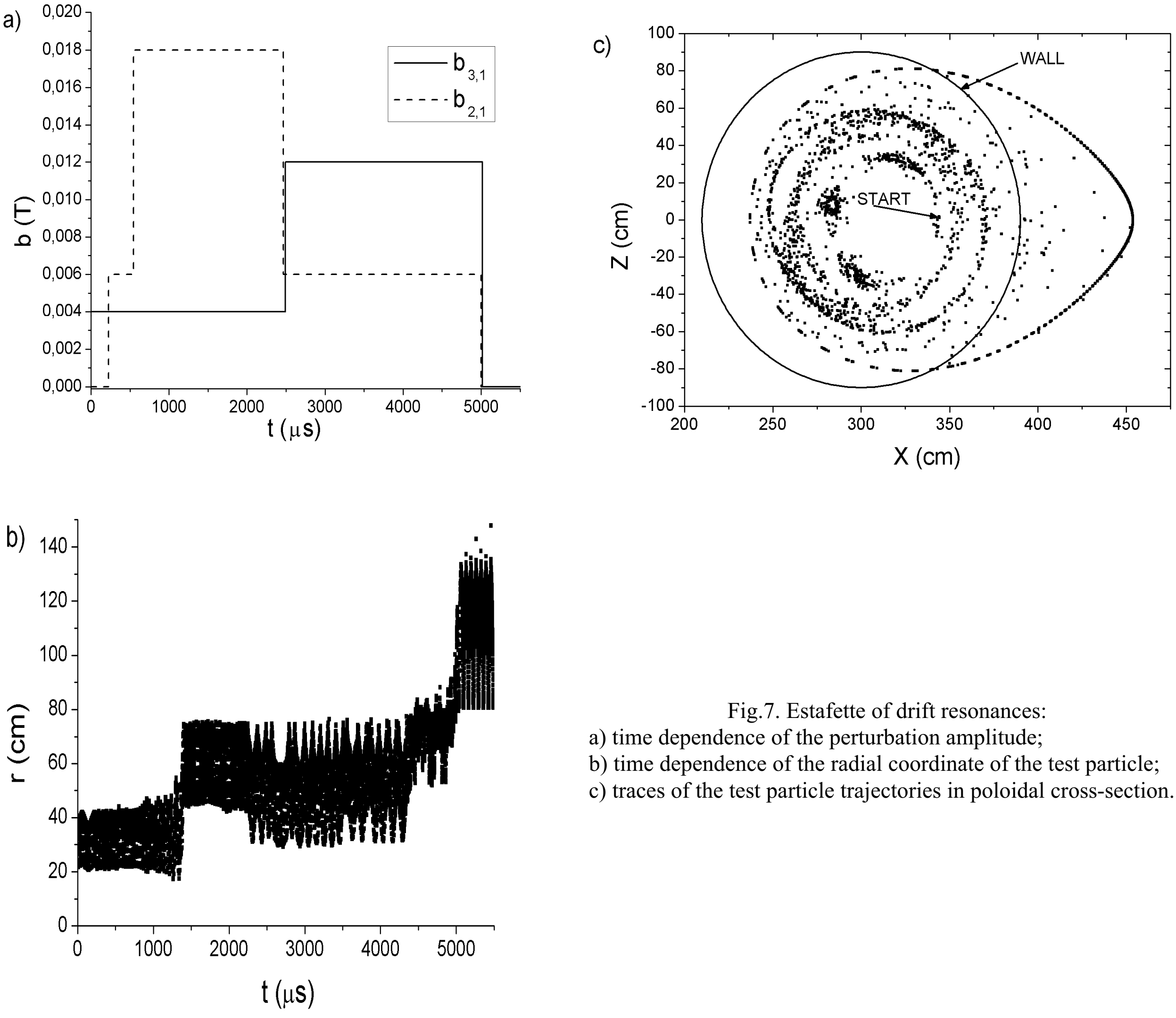

Fig.7. Estafette of drift resonances:
a) time dependence of the perturbation amplitude;
b) time dependence of the radial coordinate of the test particle;
c) traces of the test particle trajectories in poloidal cross-section.

CONCLUSION

The dependence of the drift rotational transform angle profile on particle energy was investigated. It was shown that only particles with energies lower than $W = 60\,keV$ had drift rotational transform angle with a negative central shear. The estafette of drift resonances as the method of selective transport of the particles from one plasma radius to another was developed for a tokamak with reversed shear. A number of potential applications of this method needed for a tokamak reactor have been noted, perhaps the most demanding of which is ash removal, the principal focus of this work. Numerical simulations demonstrated how the estafette of drift resonances could be used for helium ash removal in tokamaks with a reversed shear. In order to enhance the evidence some more issues can be taken into account in future. The statistic for particles with different initial conditions enclosed in some volume in phase space should be obtained. The influence of Coulomb scattering on particle motion will be also investigated with Monte Carlo method.

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ЭСТАФЕТА ДРЕЙФОВЫХ РЕЗОНАНСОВ В КОНФИГУРАЦИИ ТОКАМАКА С ОБРАЩЕННЫМ ШИРОМ

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Метод управления переносом частиц под действием магнитных возмущений с малыми тороидальными волновыми числами изучен посредством численного моделирования. Рассмотрен режим работы токамака с обращенным широм. Исследована зависимость профиля угла дрейфового прокручивания от энергии частицы. Определен диапазон энергий, соответствующих профилю угла дрейфового прокручивания с обращенным широм. Продемонстрирован вывод тестовой частицы гелия из центра плазмы на периферию.

КЛЮЧЕВЫЕ СЛОВА: управление движением частиц, эстафета дрейфовых резонансов, токамак с обращенным широм, уравнения ведущего центра, компьютерное моделирование.