EFFECT OF THE RESONANCE PHENOMENA ON HIGH ENERGETIC PARTICLE LOSSES IN CLOSED MAGNETIC TRAP WITH THE ROTATIONAL TRANSFORM OF THE MAGNETIC FIELD

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The mechanism of controlled resonant particle transport in the closed magnetic traps is studied. The resonance condition of the particle-magnetic field interaction is presented. The dependence of the resonance radial position on the particle kinetic energy W and parameter value $V_{\|}/V$ is demonstrated. The cold α-particle motion in close vicinity to the resonance position is analyzed with the use of numerical integration of the guiding center equations under Coulomb scattering.

PACS: 52.55.Pi, 52.65.Cc, 52.55.Dy, 52.35.Mw, 52.20.Hv

1. INTRODUCTION AND MOTIVATION

An essential problem of the nuclear fusion in closed magnetic traps is fusion product particle confinement. On the one hand, huge (~1 MeV) birth energy of these ions should be transferred to background plasma to maintain ignition. Under maintaining ignition it is meant the heating of new portions of fuel. On the other hand, cooled (~10 keV) ions should be removed for maintaining energy balance through decreasing radiation losses.

From the first DT experiments on JET and TFTR it became obvious that large MHD activity causes a fast ion loss fraction up to ≈ 50%, which would be intolerably large for a reactor [1, 2]. As it was shown analytically in works [3-8] resonant interaction between a spectrum of Alfven waves and α-particles can take place, leading to significant anomalous transport of the particles. Much attention is devoted to dynamics of shear Alfven waves collectively excited by energetic particles (see, e.g., [9]).

The resonant interaction is also very important for helical systems, because spectrum of these phenomena is wider due to helical symmetry. The experimental study of this problem is carried out on LHD [10-11], analytical approach is realized in Refs [3, 5].

Discovery of the super density core in plasmas on the LHD has stimulated study of a fusion helical reactor with a high density and relatively low temperature plasma [12-14], from the one hand, and, from the other hand, of different methods of α-particle confinement control in helical devices. One group of these methods is based on production of drift resonances by the resonant magnetic perturbation of certain mode [15-19].

Here the effect of Coulomb scattering on cold α-particles drift resonances is studied.

The paper is organized as follows. The model of the magnetic field and electrical field models are presented in Section 2.1. The resonance condition for system *particle-magnetic field* is analyzed numerically in Section 2.2. The cold α-particles motion in close vicinity to the resonance position is analyzed with the use of numerical integration of the guiding centre equations in Section 3. Principal conclusions are drawn in Section 4.

2. RESONANCE CONDITION IN TOROIDAL CONFIGURATION WITH THE ROTATIONAL TRANSFORM

2.1. MAGNETIC AND ELECTRICAL FIELD MODELS

The coordinates used in the present calculation are the quasi-toroidal coordinates (r, ϑ, φ). The main magnetic field is introduced in the following form

$$\mathbf{B} = B_0 R_0 / R \left\{ 0,\, r/R_0 \iota\left(r^2\right),\, 1 \right\}, \qquad (1)$$

where ι is the rotational transform, $R = R_0 + r\cos\vartheta$.

The magnetic field perturbations in general case could be written as

$$\boldsymbol{\delta}\mathbf{B} = \frac{B_0 R_0}{R} b_{m,n} \left(\frac{r}{a} \right)^{m-1} \left(\sin\Theta, \cos\Theta, 0 \right) , \qquad (2)$$

where $\Theta = m\vartheta - n\varphi$, $b_{m,n}$ is the perturbation field amplitude, m and n are the poloidal and toroidal numbers of the perturbation field, respectively.

The following expression for the electric potential is used

$$\Phi_E = \Phi_{E0} \left(1 - (r)^{\alpha_{1E}} \right)^{\alpha_{2E}} . \qquad (3)$$

Electric field was defined as $\mathbf{E} = -\nabla \Phi_E$. Such profile parameter values for further simulations are used $\Phi_{E0} = -10 kV$, $\alpha_{1E} = 8$ and $\alpha_{2E} = 2$.

2.2. RESONANCE CONDITION

To analyze the dependence of the resonance radial position from the particle kinetic energy W and parameter value $V_{\|}/V$ we use the resonance condition $\Delta = 0$ which was obtained in [19] for chosen models of magnetic and electrical field. The analytical expression for Δ has the form

$$\Delta = \frac{Wm(m-1)}{2Ma^2} \left\{ \begin{array}{l} \dfrac{2W}{M\omega_c^2} \left(1 - \dfrac{\upsilon_{\|}^2}{\upsilon^2} \right)^2 - \left(r \dfrac{\upsilon_{\|}}{\upsilon} \left(\iota - \dfrac{n}{m} \right) - R_0 \dfrac{\upsilon_{DE}}{\upsilon} \right) \times \\ \times \left(r \dfrac{\upsilon_{\|}}{\upsilon} \left(\iota - \dfrac{n}{m-1} \right) - R_0 \dfrac{\upsilon_{DE}}{\upsilon} \right) \end{array} \right\} ,(4)$$

Series: Plasma Physics (14), p. 19-21.

where $W, M, v, v_{\|}$ are kinetic energy, particle mass, particle velocity and longitudinal component of velocity, respectively. $v_{DE} = cE_r/B_0$ is the electric drift velocity and $\omega_c = ZeB/(Mc)$ is the cyclotron frequency.

The resonance condition takes place at two values of the radial positions (there exist two roots) under the perturbations with "wave" numbers $m = 3, n = 1$.

The analysis of the resonance condition is presented on the Fig.1 and Fig.2.

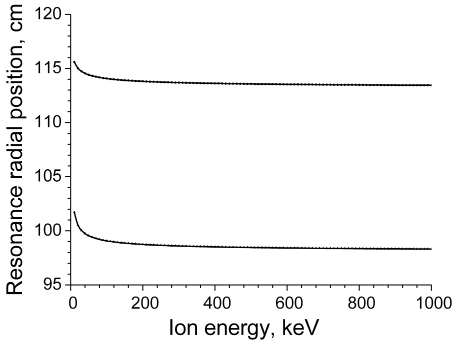


Fig.1. Resonance radial position versus ion energy

One can see from the Fig.2 and Fig.3 that the radial position of the resonances

- weakly depends on the particle energy in the range $50keV \le W \le 1MeV$;
- weakly depends on the parameters $V_{\|}/V$ for the values about unity, but for values about zero the situation is opposite, in particular, for negative values resonance shifts to the plasma core.

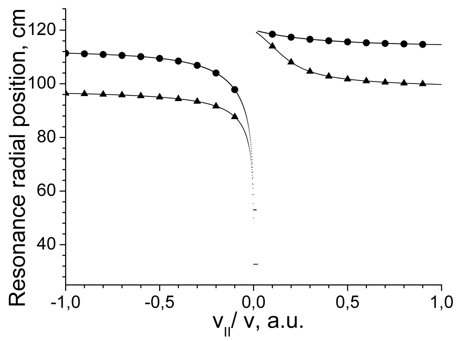


Fig.2. Resonance radial position versus parameter value $V_{\|}/V$

It should be noted that during its motion α-particle collides with background plasma particles, hence its parameter $V_{\|}/V$ decreases. This could effect on particle drift resonance: the particle could turn out in resonance with magnetic field perturbation, and escape from resonance. The effect of Coulomb Scattering will be shown in the next section.

3. A-PARTICLE DRIFT RESONANCES

In the previous work [19] it was shown that if the resonance conditions take place at the plasma periphery, then the removal of the cold α-particles is noticeable. It should be noted that the characteristic time of the studied processes is of the order 1–10 milliseconds and Coulomb scattering should be taken into account.

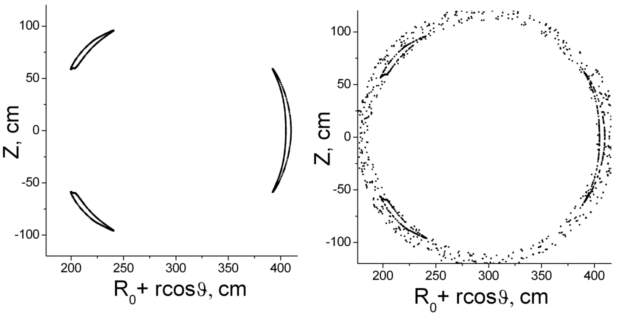
The effect of collisions in plasma is expressed in the guiding center equations through the following term [20]

$$\left\langle \frac{d\mathbf{p}}{dt} \right\rangle = -\frac{4\pi Z^2}{v^3}\mathbf{V}_{g.c.}\sum_{*}\frac{L\left(Z^*\right)^2\left(M+M^*\right)}{MM^*}n^*\Phi_1\left(b^*v\right), (5)$$

where $\Phi_1\left(b^*v\right) = \Phi(x) - x\Phi'$, and $\Phi(x)$ is the error function; $b^* = \sqrt{M^*/2T^*}$; L is Coulomb logarithm; Z, M are particle charge and mass, T, n are background plasma temperature and density, respectively; superscript * designates variables which relate to background plasma.

For simulation of the α-particle motion following initial parameter values were chosen $W = 100keV$, $V_{\|}/V = 0.9$, $r_0 = 109$ *cm*; $\theta_0 = 0$, $\varphi_0 = 0$ and 50% mixture DT plasma parameters: $n^* \approx 10^{13} cm^{-3}$, $T^* = 20keV$.

Parameters of magnetic configuration were chosen similar to those which are used in JET: $B_0 = 2\text{Ч}0^4 G$, $a = 120cm$, $R_0 = 296cm$, $\iota = 1 - 0.75\cdot(r/a)^2$, $b_{mn} = 30$ *G*.



a *b*

Fig.3. The drift islands with the drift transform $\iota^* = 1/3$ in the vertical cross-sections of the torus w/o collisions (a); and under Coulomb scattering (b)

Under the same initial conditions α-particle deviates from the initial surface due to Coulomb scattering on the contrary to the case without collisions (Fig.3).

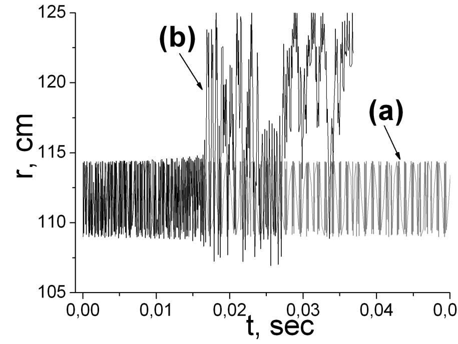


Fig.4. Radial position of the α-particles with the initial energy $W = 100$ keV versus time w/o collisions (a); and under Coulomb scattering (b)

As it can be seen from Fig.4(a) the radial coordinate of the α-particle is oscillating near drift resonance position during 50 msec. We mean that the equation $\Delta = 0$ is satisfied. But we see from Fig.4(b) that in the presence of the collisions the same particle during the period till t=15 msec is in the resonance interaction with the perturbing field, and then leaves the resonance and deviates to the larger distances from the initial surface.

Summarizing, the conclusion is done that the Coulomb scattering could lead to both formation and destruction of the drift islands.

4. SUMMARY AND DISCUSSIONS

The interaction of α-particle with magnetic perturbation of small amplitude leads to resonant structures formation (*drift islands*).

The resonance condition analysis shows that radial position of the drift resonance is sensitive to the particle kinetic energy in the range 10-100 keV. For small negative value of the ratio $V_{\|}/V$, the resonance occurs near plasma core.

The particle collisions could lead to both formation and destruction of the drift resonance. Besides that resonant interaction with magnetic field perturbation together with Coulomb scattering increase transport of energetic particles at the plasma edge.

These mechanisms in couple can be used for the removal controlling of cold the α-particles outward transport from the confinement volume.

ACKNOWLEDGEMENTS

Authors thank Prof. Igor Girka for continuously attention to their work, support and useful suggestions and Dr. Oleg Shyshkin for fruitful discussions and invaluable advices.

The research is supported by Science and Technology Center in Ukraine, Project # 3685.

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Article received 22.09.08

ВЛИЯНИЕ РЕЗОНАНСНЫХ ЯВЛЕНИЙ НА ПОТЕРИ ВЫСОКОЭНЕРГЕТИЧНЫХ ЧАСТИЦ В ЗАМКНУТОЙ МАГНИТНОЙ ЛОВУШКЕ С ВРАЩАТЕЛЬНЫМ ПРЕОБРАЗОВАНИЕМ МАГНИТНОГО ПОЛЯ

Ю.К. Москвитина, А.А. Шишкин

Изучен механизм управляемого переноса резонансных заряженных частиц в замкнутых магнитных ловушках. Представлено резонансное условие в случае взаимодействия частица-магнитное поле. Исследована зависимость радиального положения резонанса от кинетической энергии W и значения параметра $V_{\|}/V$ частицы. Проанализировано движение α-частицы вблизи резонанса путём численного интегрирования уравнений движения ведущего центра при наличии кулоновского рассеяния.

ВПЛИВ РЕЗОНАНСНИХ ЯВИЩ НА ВТРАТИ ВИСОКОЕНЕРГЕТИЧНИХ ЧАСТИНОК В ЗАМКНУТІЙ МАГНІТНІЙ ПАСТЦІ З ОБЕРТАЛЬНИМ ПЕРЕТВОРЕННЯМ МАГНІТНОГО ПОЛЯ

Ю.К. Москвітіна, О.О. Шишкін

Вивчено механізм керованого переносу резонансних заряджених частинок в замкнутих магнітних пастках. Представлено резонансну умову в разі взаємодії частинка-магнітне поле. Досліджено залежність радіального положення резонансу від кінетичної енергії W та значення параметра $V_{\|}/V$ частинки. Проаналізовано рух α-частинки поблизу резонансу шляхом чисельного інтегрування рівнянь ведучого центру за наявності кулонівського розсіювання.