TRAPPED ALPHA-PARTICLE ORBITS UNDER THE EFFECT OF DRIFT WAVES

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1. Introduction

One of the main issues of fusion reactors are good confinement of “hot“ α-particles (with energy 3520 *keV*) and removal of “cold“ α-particles (with energy y 352 *keV*) in order to prevent ash accumulation. In a Helias Reactor ($R = 22\ m,\ a_{pl} = 1.8\ m,\ B_0 = 5T$) [1,2] a relatively large fraction of α-particles is trapped and above $<\beta>=2\%$ the confinement of these particles is improved due to poloidal magnetic drift. These conditions are favorable for confining “hot“ α-particles, but also “cold“ trapped α-particles are well confined. However, confinement of these particles can be destroyed by plasma fluctuations. For this reason we investigate the influence of the low-frequency drift waves ($\omega < 10^5$ *rad/sec*) on the orbits and confinement of “hot“ and “cold“ trapped α-particles. A numerical code based on the Hamiltonian guiding center drift orbit formalism is used to study particle motion in Helias Reactor with $\beta(0) = 3\%$. Especially we address those particles which are well confined at this low value of β.

2. Formalism

In the present paper “low-frequency“ means frequencies which are low compared with the cyclotron frequency of α-particles $\omega_\alpha = 2eB_0/mc = 2.4*10^8$ *rad/sec*. For such perturbations we can use the guiding center approximation for particle motion in a stationary magnetic field [3,4,5]. In the case when unperturbed toroidal magnetic field forms nested magnetic surfaces the coordinate system is closely connected with flux coordinates (ψ,θ,ζ) [6,7] in terms of which the magnetic field **B** has the following representation

$$\mathbf{B} = g(\psi)\nabla\varsigma + I(\psi)\nabla\theta + \beta^*(\psi,\theta,\varsigma)\nabla\psi \qquad (1)$$

$$\mathbf{B} = \nabla\psi\times\nabla\theta + \nabla\varsigma\times\nabla\psi_p(\psi) \qquad (2)$$

The vector potential associated with magnetic field (1)-(2) is $\mathbf{A} = \psi\nabla\theta - \psi_p(\psi)\nabla\varsigma$. The flux functions ψ and ψ_p determine the rotational transform of the field line $\iota(\psi) = \frac{d\psi_p(\psi)}{d\psi}$.

The guiding center motion is described by the system of canonical equations derived from the Hamiltonian [3,7]

$$H = mv_{II}^2/2 + \mu B + q\Phi \qquad (3)$$

which coincides with total energy of the particle *W*. The functions $I(\psi)$, $g(\psi)$, $\iota(\psi)$ and $B(\psi,\theta,\zeta)$ which are obtained by equilibrium code [8,9] completely define the particle orbits in coordinates (ψ,θ,ζ).

3. Drift waves as an electric perturbation

To describe the influence of drift wave we add a perturbation in the form of electrostatic wave, which has electric field $\mathbf{E} = -\nabla\Phi$ and zero magnetic field. We concentrate on density gradient drift waves which are particular type of electrostatic waves. We focus our attention on waves which propagate perpendicular to the magnetic field on magnetic surfaces with rational values of rotational transform ι. The dot-product **k**·**B**=0 creates following condition for covariant components of propagating vector: $k_\theta \iota + k_\varsigma = 0$, where $\iota = n/m$ (Fig.1*a*). If $k_\theta = m_\Phi = l \cdot m$ (*l* is integer) is poloidal mode number, then $k_\varsigma = -\iota\, m_\Phi$ and potential takes the form [10,11]

$$\Phi = \Phi_0 \cos(k_r r)\cos(m_\Phi(\theta - n/m\,\varsigma) - \omega_* t + \delta) \qquad (4)$$

with the drift frequency

$$\omega_* = \frac{cT_e}{eB}\frac{m_\Phi}{r}\left(-\frac{dn}{ndr}\right) \qquad (5)$$

After elimination of the gyrofrequency the highest frequency in the system is the frequency of particle oscillations in the magnetic well ω_b (bounce frequency), which depends on location of magnetic well, particle energy *W* and pitch angle $\lambda = v_{II}/v$ (Fig.1*b*). On Fig.1*c* one can see drift frequency (6) in Helias Reactor versus poloidal mode number m_Φ in comparison with bounce frequency of trapped "cold" and "hot" α-particles ω_b^{cold} and ω_b^{hot}.

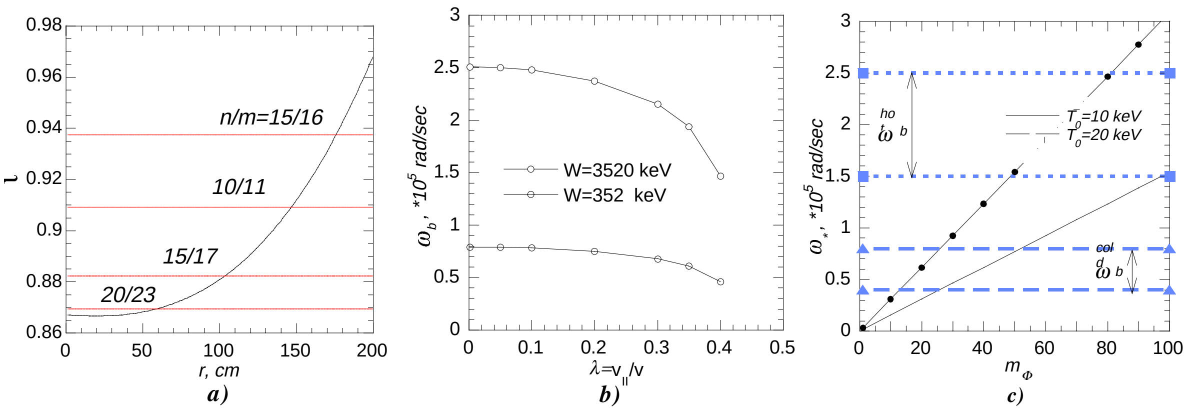

Fig. 1. ***(a)*** Rotational transform ι in Helias configuration with $\beta(0)$=3%. ***(b)*** The bounce frequency versus pitch angle λ of the trapped α-particles on the surface with *r*=80 cm. ***(c)*** Relation between drift frequency ω_*(5) and bounce frequency of trapped α-particles.

To estimate drift frequency in Helias Reactor we model electron temperature and density profiles in the forms [6,7] $T_e = T_0\left(1-(r/a)^2\right)^2, n = n_0\left(1-(r/a)^6\right)^3$, $T_0 = 10 \div 20$ keV and radius *r/a = 0.7*, where the density gradient is large. One can see that drift waves with poloidal numbers $m_\Phi = 15 \div 50$ have a frequency of the same order as the bounce frequency of “cold“ α-particles, and the frequency of those with $m_\Phi = 50 \div 100$ is of the same order as the bounce frequency of “hot“ α-particles. Because of such difference one may expect corresponding resonances. Numerical integration of the canonical equations of the Hamiltonian (3) shows that such resonances do exist (Fig.2,3) for electric fields with a maximum amplitude $E_0 = |E_{max}| = 30 \div 45\ V/cm$. The superposition of magnetic field gradient drifts and electric drifts causes large radial deviation of trapped particle orbits from initial magnetic surface and fast “cold“ α-particle losses from the plasma volume. In the presence of highest harmonics of magnetic field *B* bounce frequency ω_b is functions on particle coordinates and owing to gradient drift it varies considerably during particle motion, which gives the chance for one particle be resonant with several waves. A deviation from original orbit due to resonance with the first wave (Fig.3*a*) may create condition for fast losses owing to resonance with a second wave (Fig.3*b*). It is important to demonstrate that waves which cause the described resonances, do not strongly effect on “hot“ α-particle motion (Fig.2*c*,3*c*). The “hot“ α-particle orbits experience little changes, but neither large deviation nor increased losses are observed. It means that due to drift waves it is possible to remove “cold“ α-particles without increasing “hot“ α-particle losses, which may be useful for preventing ash accumulation.

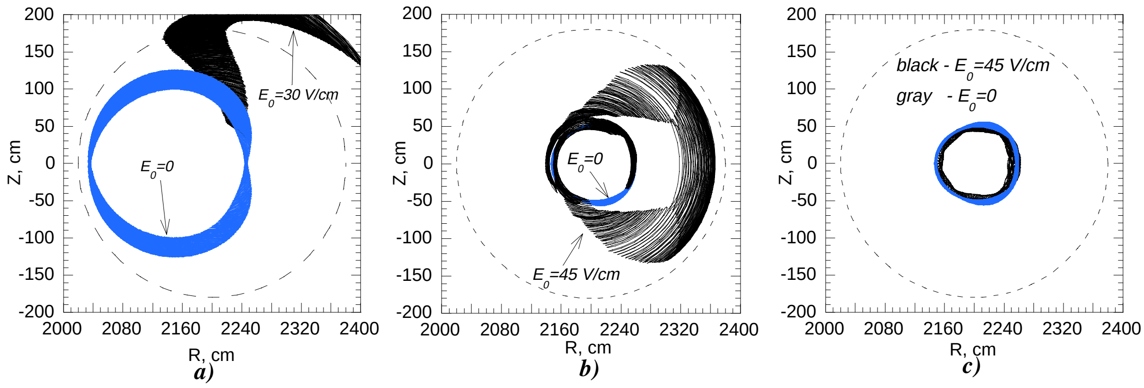

Fig. 2. Effect of electric perturbation due to drift wave with potential (4), *n/m*=20/23, poloidal mode number m_Φ= 23 and drift frequency $\omega_* = \omega_b = 0.65 * 10^5$ rad/sec on “cold“ trapped α-particle orbit: ***(a)*** the particle starts in the bottom of 2nd magnetic well on the surface with r = 60 cm with pitch angle λ = 0.3; ***(b)*** the particle starts in the bottom of 1st magnetic well on the surface with r = 60 cm with pitch angle λ = 0.33; ***(c)*** the same as Fig.2b, but for “hot“ trapped α-particles with energy W = 3520 keV.

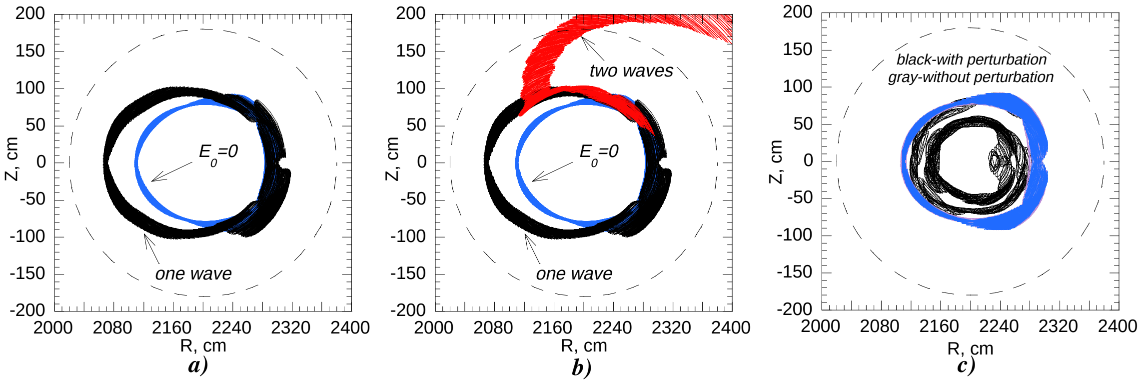

Fig. 3. Effect of electric perturbation due to drift waves with potential (4), E_0 =45 V/cm and drift frequencies $\omega_* = \omega_b$ on "cold" trapped α-particle orbit. The particle with pitch angle λ = 0.33 starts in the bottom of 2nd magnetic well on the surface with *r*=104 cm. ***(a)*** one wave with *n/m*=15/17, m_Φ=34 and frequency $\omega_{*1} = \omega_b$ = 0.6*10^5 rad/sec; ***(b)*** two waves: the first is as in (a), the second with *n/m*=10/11, m_Φ=33 and frequencies $\omega_{*2} = \omega_b$ = 0.8*10^5 rad/sec; ***(c)*** the same as Fig.3b, but for "hot" trapped α-particles with energy *W* = 3520 keV.

4. Summary

Analytical estimations and numerical integration of canonical equations based on the guiding center Hamiltonian theory allow us to conclude, that resonances between trapped "cold" α-particles and drift waves with poloidal mode number $m_\Phi = 15 \div 50$ do occur when the electric field of the wave has an amplitude as large as $E_0 = |E_{\max}| = 30 \div 45\ V/cm$. It is shown that due to this resonance drift waves can cause appreciable losses from plasma region of "cold" trapped α-particles (with energy 352 *keV*) without destroying the confinement of "hot" α-particles (with energy 3520 *keV*). This fact offers the chance of energy-selective transport mechanism by means of the drift waves, which may be useful for ash removal.

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