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Superbanana Orbits in Helias Reactor Caused by the Electromagnetic Perturbations

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Introduction. One of the main features of a Helias reactor [1,2] (R *= 22 m*, a_{pl} *= 180 cm*, B_0 *= 5 T*) is a good confinement of trapped particles in the finite β case. It is provided by eliminating superbanana orbits and closing the orbits of circulating bananas by means of enhanced poloidal magnetic drift [3,4]. Time independent and time dependent electromagnetic perturbations can strongly change the particle orbits, their confinement and redistribution. For this reason we study the motion of the trapped particles in the Helias configuration with $<\beta>=5\%$ under the effect of static and low frequency perturbations. Since α-particle confinement and ash removal are of great importance for operating of a fusion reactor, we investigate α-particles with energies *3520 keV ("hot"), 352 keV ("cold")* and *35 keV ("ash")*. The Helias configuration with $<\beta>=5\%$ has *5/6* resonance surface on $r\approx 120$ *cm* inside the plasma column which can cause development of MHD instabilities, therefore our interest is focused on the perturbations with mode numbers *(6,5)* and maximum value of radial profile on the resonance magnetic surface. For comparison the effect of the perturbation with mode numbers *(2,0)* and the maximum value on $r=80$ *cm* is also presented.

Formalism. In present work we consider perturbations with frequencies which are small in comparison with the cyclotron frequency of α-particles. For such perturbations we can use formalism based on the normalized guiding center Lagrangian [5,6]. We focus our attention on trapped particles (not transition ones) which permanently stay in one magnetic well. For such particles the averaging over banana orbit can be applied [7,8] to obtain equations of the banana center (ψ_{bc},θ_{bc}) orbit

$$\frac{d\psi_{bc}}{dt} = \frac{\partial J}{\partial\theta}\Big/\frac{\partial J}{\partial W}, \quad \frac{d\theta_{bc}}{dt} = -\frac{\partial J}{\partial\psi}\Big/\frac{\partial J}{\partial W} \quad \text{, where} \tag{1}$$

$$J = \frac{1}{2\pi}\oint\left(A_\zeta(\mathbf{x},t) \pm B_\zeta(\mathbf{x},t)/B(\mathbf{x},t)\cdot\sqrt{2(W-\mu B(\mathbf{x},t)+\Phi(\mathbf{x},t))}\right)d\zeta \tag{2}$$

We use flux coordinate system $\mathbf{x}=(\psi,\theta,\zeta)$ [9,10], the flux variable ψ refers to the average radius r as $\psi=1/2(r/R_0)^2$. Electromagnetic perturbations are included through the scalar potential $\Phi(\mathbf{x},t)$, toroidal components of vector potential $A_\zeta(\mathbf{x},t)$ and magnetic field $B_\zeta(\mathbf{x},t)$ and magnetic field strength $B(\mathbf{x},t)$. In unperturbed case, with equilibrium magnetic field and zero electric potential, the particle energy W and magnetic moment μ are constants and equations (1) are equivalent to J-contours, which are poloidally closed in the Helias configuration with finite plasma pressure due to the optimization [4].

Trapped particles in Helias reactor with $<\beta>=5\%$. To study particles orbits we take equilibrium magnetic field strength in a Fourier expansion form [1,2,9,10]

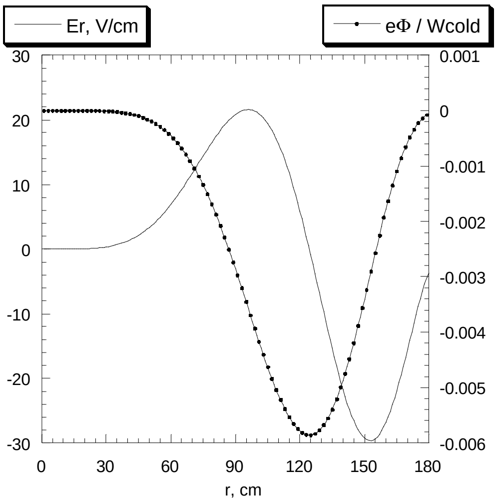
$$B^{eq}(\psi,\theta,\zeta) = 1 + b_{0,0} + b_{0,1}\cos(M\zeta) + \sum_{l=0}^{\infty} b_{0,l}\cos(lM\zeta) + \sum_{k=1}^{\infty}\sum_{l=-\infty}^{\infty} b_{k,l}\cos(lM\zeta - k\theta) \tag{3}$$

in which we reduce the number of harmonics to *53* in order to avoid the effect of the modular coil ripples. We launch particles in bottom of the same magnetic well with different initial pitch angle $\lambda=v_{\parallel}/v$ and from different magnetic surfaces. In equilibrium magnetic field of Helias reactor with $<\beta>=5\%$ particles with initial pitch angle $1>\lambda\geq 0.4$ are passing ones, those with $0.4>\lambda\geq 0.35$ are transition ones, and those with $\lambda<0.35$ are trapped in one magnetic well. They form only passing banana orbits and move along closed contours. The banana center orbits of the deeply trapped particles which start near the plasma edge are also closed inside the plasma region. Though their deviation from starting magnetic surface is large, it directs inward the plasma and is not dangerous for particle confinement.

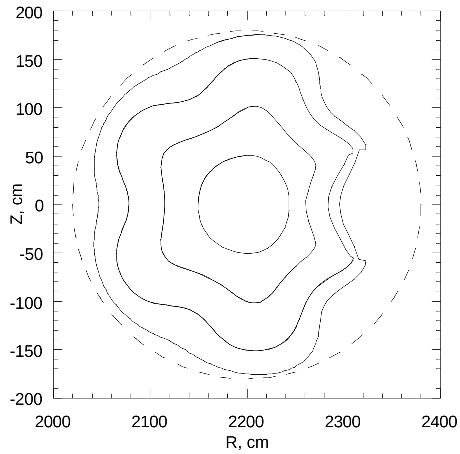
Superbanana orbits caused by electromagnetic perturbations. In the present paper we study the influence of electrostatic perturbations with $\mathbf{E}=-\nabla\Phi$ and time independent Alfvén type magnetic perturbations with $\delta\mathbf{B}(r,\theta,\zeta)=\nabla\times(\phi\mathbf{B}^{eq})$. We restrict the amplitudes of perturbations by maximum value of magnetic field $\delta B/B^{eq}=10^{-3}$ and maximum value of electric field $|E|\approx 30\ V/cm$, which is six times less then ambipolar electric field in the Helias reactor [1,2]. The scalar potential $\Phi(r,\theta,\zeta,t)$ and scalar function $\phi(r,\theta,\zeta)$ have general form

$$f(r,\theta,\zeta,t)=f_0(r)\cos(m\theta-n\zeta-\omega t+\delta) \qquad (4)$$

The first perturbation is electrostatic one with mode numbers $m=6$ and $n=5$ and potential $\Phi(r,\theta,\zeta,t)$ with peak value of amplitude on magnetic surface with $r\approx 120\ cm$, where rotational transform ι has rational value $5/6$ (*Fig.1a*). Such a perturbation does not disturb *"hot"* α-particles motion, slightly modifies orbits of *"cold"* α-particles (*Fig.1b*) and significantly changes orbits of *"ash"* α-particles (*Fig.2a*).



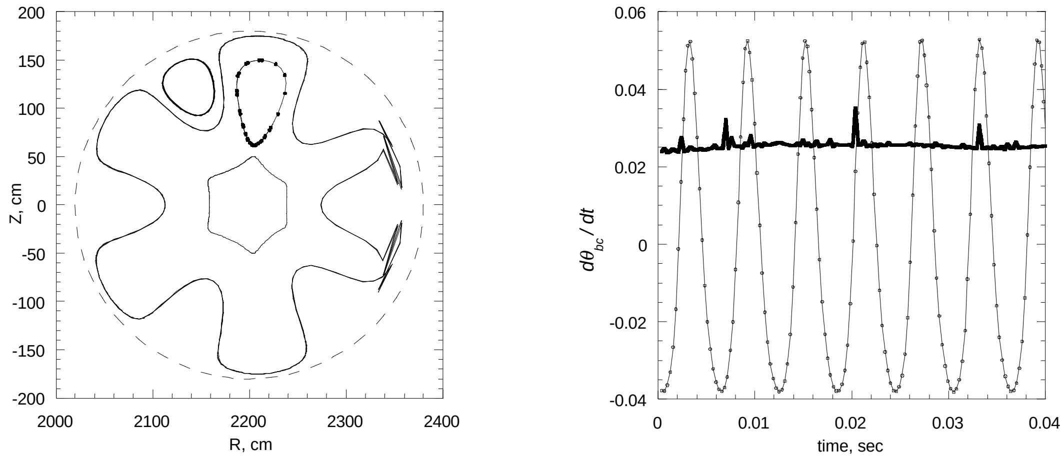
a



b

Fig.1. *a) Radial profiles of the electric field (left) and the potential (right); b) banana center orbits of "cold" α-particles under the effect of the time independent electrostatic perturbation with mode numbers (6,5) and radial profiles as in Fig.1a, particles start in the same magnetic well with initial pitch angle λ=0.3*

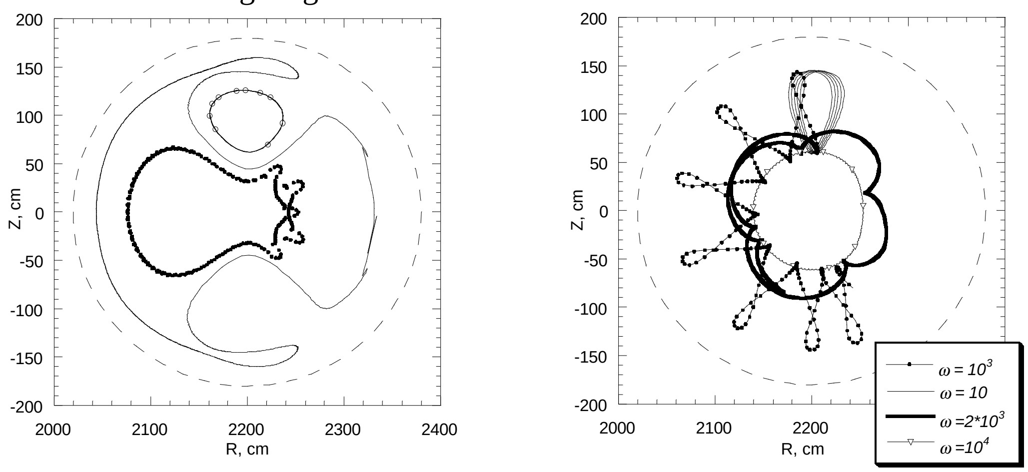
All the banana center orbits have large deviation (about *100 cm*) from starting magnetic surface. Some of them, due to poloidal trapping in the potential well of electric field, form closed orbits like islands. These trajectories are superbananas because the poloidal velocity of the banana center $d\theta_{bc}/dt$ becomes zero (thin line with black circles in *Fig.2b*, thick line is unperturbed case). If we change the phase δ or the sign of the potential the condition $d\theta_{bc}/dt=0$ is never fulfilled and the trajectory remains circulating banana, though its deviation from unperturbed trajectory is very large. It is important to say, that more deeply trapped particles have smaller poloidal drift velocity and require smaller perturbation to form superbanana orbit.



a *b*

Fig.2. *a) Banana center orbits of the "ash" α-particle under the effect of the time independent electrostatic perturbation with mode numbers (6,5) and radial profiles as in Fig.1a; b) poloidal drift velocity of the superbanana island (thin curve with black circles, thick curve is unperturbed case).*

For comparison we apply another time independent electrostatic perturbation which has mode numbers *m=2* and *n=0* and the maximum value on magnetic surface with *r=80 cm* (*Fig.3a*). The size of the island in radial direction is approximately the same (about *100 cm*), but in poloidal direction it becomes much large. When we change the sign or the phase δ of the potential the island structure appears for particles with another starting positions, but its size is still very large (about *110 cm*). If the perturbation is time dependent ($\omega \neq 0$) the island slowly rotates in poloidal direction (*Fig.3b*). When frequency of the perturbation ω becomes large then the frequency of banana center rotation around the island, but it is still smaller then bounce frequency of the particle, the superbanana structure disappears (thick curve in *Fig.3b*) and deviation from starting magnetic surface decreases.

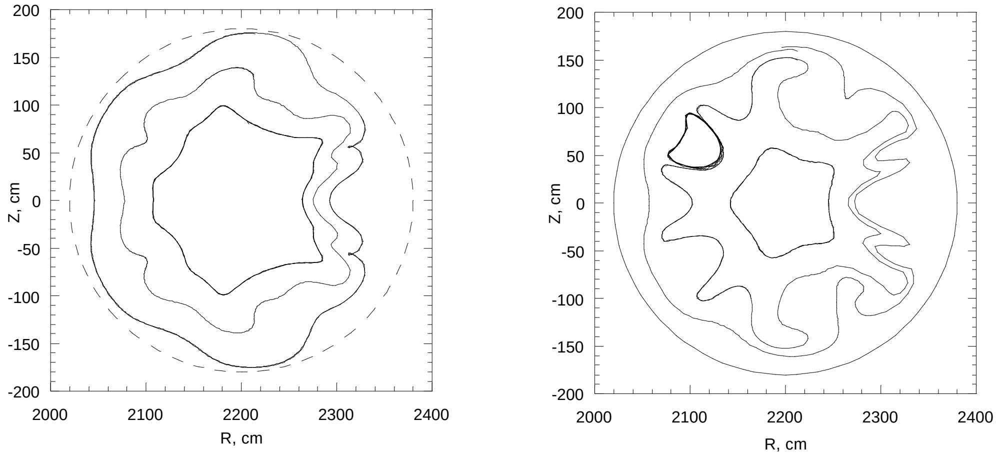


a *b*

Fig.3. *a) Banana center orbits of "ash" α-particles under the effect of the time independent electrostatic perturbation with mode numbers (2,0); b) the same island structure as in Fig.2a, but with non-zero frequency of perturbation ω (rad/sec).*

The third perturbation is time independent magnetic one $\delta\mathbf{B}(r,\theta,\zeta)=\nabla\times(\phi\mathbf{B}^{eq})$, with $\phi(r,\theta,\zeta)$ in the form (4), peak value of amplitude on magnetic surface with $r\approx 120$ *cm* and mode numbers *m=6* and *n=5*. The most important feature of such a perturbation is that its effect on banana center orbits does not depend on particle energy. For all kinds of trapped α-particles influence of the magnetic perturbation becomes noticeable at value $\delta B/B^{eq}=5\cdot 10^{-4}$

(*Fig.4a*), at value $\delta B/B^{eq}=10^{-3}$ (*Fig.4b*) superbanana orbits appear and deviation of the banana center orbit from starting magnetic surface becomes about *90 cm*.



a *b*

Fig.4. *Banana center orbits of the α-particles under the effect of time independent magnetic perturbation with mode numbers (6,5) and peak value of amplitude $\delta B/B^{eq}$=5e-4 (a) and $\delta B/B^{eq}$=1e-3 (b).*

Summary. It is shown that in the equilibrium magnetic field of the Helias configuration considered in the present paper without perturbations all trapped particles form only poloidally passing bananas. The banana center orbits are closed inside the plasma column, which provides the absolute confinement of trapped particles. Due to the electromagnetic perturbation the poloidal drift can be suppressed and superbanana orbits can appear in the configuration as a result of the poloidal trapping of the banana orbit center. Poloidal size of superbanana orbits depends on poloidal mode number *m*, the deviation from the original orbit and the width of the superbanana in radial direction depend on the radial profile and amplitude of the perturbation. If the perturbation does not go to zero on the plasma edge particles with such orbits can be easily lost. The effect of electric perturbation is strongly selective in particle energy, which can be useful for ash removal. An electrostatic perturbations with maximum value of the field $|E| \approx 30$ *V/cm* do not effect trapped *"hot"* α-particles, slightly change trajectory of *"cold"* α-particles, and significantly perturb orbits of *"ash"* α-particles, which have a deviation from starting magnetic surface about *100 cm*. The same effect one can expect for thermal deuterium and tritium particles. The influence of time independent magnetic perturbation does not depend on particle energy. For all trapped α-particles magnetic perturbation with maximum amplitude $\delta B/B^{eq}=10^{-4}$ is negligible, but that with $\delta B/B^{eq}=10^{-3}$ causes large excursions of banana center orbits in radial direction (about *90 cm*). It means that due to such a perturbation the radial diffusion of *"hot"* α-particles can be increased and the heating efficiency can be diminished in comparison with neoclassical case.

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