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Alpha-Particle Confinement in $l=3$ Reactor Sized Helical System with the Small Aspect Ratio

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Abstract

The way to control the alpha-particle motion in $l=3$ helical reactor is considered. It is shown that the externally applied transverse magnetic field can decrease the deviation of alpha-particles from the initial magnetic surfaces.

Keywords:

fusion helical reactor, alpha-particles, confinement, magnetic axis shift, compact system

1. Introduction

In the usual magnetic system schemes of the helical type reactor the aspect ratio $R/a_{\rm h}$, where R and $a_{\rm h}$ are the large and the small radii of the helical coils winding, is taken from 4 to 8 [1-4]. The Force-Free-Helical Reactor (FFHR) in its reference version [1-3] has the following parameters: $R=20$ m, $a_{\rm h}=3.3$ m, $l=3$, $m=18$; here l is the number of the helical winding poles and m is the number of the magnetic field periods on the torus length. The condition of the force-free-like helical windings $\gamma=ma_{\rm h}/lR=1$ is satisfied. Here we consider the alpha-particle motion in FFHR in its reference version and in its more compact case [1,5], particularly, the effect of the transverse magnetic field on the alpha-particle confinement is under study.

2. Control of the Toroidal Field Gradient Effect on the Particle Motion with the Transverse Magnetic Field

First of all we shall give the qualitative picture of the effect that can be expected. The magnetic field in the helical system can be described as $\boldsymbol{B}=\nabla\Phi$ with the scalar potential

$$\Phi = B_0\left[R\varphi - \frac{R}{m}\sum_{n,m}\varepsilon_{n,m}(r/a_h)^n \sin(n\vartheta - m\varphi)\right],$$

where B_0 is the magnetic field at the circular axis, r, ϑ, φ, are "quasitoroidal" coordinates connected with the circular axis of torus with the metric coefficients: $h_r=1$, $h_\vartheta=r$, $h_\varphi=R+r\cos\vartheta$; $\varepsilon_{n,m}$ are the coefficients of the harmonics of the magnetic field.

The transverse magnetic field ($B_\perp$) is the residual one from the compensation of the transverse magnetic field of the unidirectional helical coil currents with the external transverse magnetic field from the vertical field coils. Depending on its sign and value this field shifts the magnetic axis of the configuration inside or outside the torus and changes the shape of the magnetic surfaces, the modulation of the magnetic field along the force line. Some features can be described with the magnetic flux surface function [8]

$$\Psi = B_0\left[(r/a_{\rm h})^2 + \sum_{n,m}\Psi_{n,m}(r/a_{\rm h})^n \cos(n\vartheta - m\varphi)\right],$$

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which contains not only main (principal) helical harmonic with the "wave" numbers (l, m) but the satellite harmonics with (l+1, m) and (l−1, m) − so called sidebands; $\Psi_{n,m}$ are the functions of the $\varepsilon_{n,m}$. The principal role of the satellite harmonics is to decrease or increase the radial drift of the trapped particles in dependence on the sign and value of the ratios $\varepsilon_{l-1,m}/\varepsilon_l$, $\varepsilon_{l+1,m}/\varepsilon_l$ [7,9]. The effect of the satellite harmonics on the high energy particle confinement (very similar to σ-optimization [7]) can be expected if the transverse magnetic field is used.

For the trapped particles with the use of the longitudinal adiabatic invariant $j_{\parallel}=\oint v_{\parallel}\mathrm{d}l$ it is possible to evalute the radial drift velocity of the banana center $\frac{\mathrm{d}\rho_0}{\mathrm{d}t}\propto\frac{\partial J_{\parallel}}{\partial\theta_0}$. Here ρ_0 and θ_0 are the coordinates of the banana center in the system of coordinates connected with the shifted magnetic axis. Using the analytical expression of $\boldsymbol{B}$ and $J_{\parallel}$ [9] we can present $\frac{\partial J_{\parallel}}{\partial\theta_0}$ in the following form

$$\frac{\partial J_{\parallel}}{\partial\theta_0}\propto\frac{\rho_0}{R\left(1+\frac{\Delta}{R}\right)}\sin\theta_0+$$

$$\frac{\varepsilon_{3,m}}{a_h^3}\rho_0^3\frac{6\Delta\sin\theta_0}{\sqrt{\rho_0^2+6\Delta\rho_0\cos\theta_0+\Delta^2}}\left[\frac{E(q^2)}{K(q^2)}-\frac{1}{2}\right],$$

where Δ is the shift of the magnetic axis, $\varepsilon_{3,m}$ is the amplitude of the main helical harmonic (ℓ=3), $E(q^2)$ and $K(q^2)$ are the elliptic integrals of the 1st and the 2nd kind of the parameter q^2. If $\Delta<0$ (magnetic axis is shifted inside) the second term is negative and the velocity $d\rho_0/dt$ for the deeply trapped particles ($q^2\ll1$) reduces as far as $3\varepsilon_{3,m}(\rho_0/a_h)^3(|\Delta|/\rho_0)$ is substracted from $(\rho_0/R)/(1+|\Delta|/R)$. If we take Δ/R, Δ/ρ_0 as small parameters under $R=20$ m, $a_h=3$ m, $|\Delta|=0.4$ m, $\rho_0=0.8$ m, $\varepsilon_{3,m}=0.76$ for $\mathrm{d}\rho_0=\mathrm{d}t$ we obtain the ratio

$$\mathrm{d}\rho_0/\mathrm{d}t|_{\Delta>0}:\ \mathrm{d}\rho_0/\mathrm{d}t|_{\Delta=0}:\ \mathrm{d}\rho_0/\mathrm{d}t|_{\Delta<0}=0.06:0.04:0.018.$$

For the passing particles the evaluation of the drift velocity $v_{\mathrm{D}}\propto[\boldsymbol{B}\nabla\mathrm{B}]$ along the force line of the magnetic field leads us to the following expression

$$v_{\mathrm{D}}\propto-\frac{1}{R}+\frac{1}{2a_{\mathrm{h}}}\left(\frac{Rl}{ma_{\mathrm{h}}}\right)^2\varepsilon_{l,m}^{\ 2}\left[\frac{\varepsilon_{l-1,m}}{\varepsilon_{l,m}}\frac{(l-1)^2}{l}r_0^{\,l-2}+\frac{\varepsilon_{l+1,m}}{\varepsilon_{l,m}}(l+1)r_0^{\,l-1}\right].$$

Here the relation $[\boldsymbol{B}\nabla B]_Z=[\boldsymbol{B}\nabla B]_r\sin\vartheta+[\boldsymbol{B}\nabla B]_{\vartheta}\cos\vartheta$ and the dependence of the radial coordinate of the force line on the angular variables, which can be obtained from the expression for Ψ, are used. The reduction of the drift velocity of the passing particles can be expected when $\varepsilon_{l-1,m}/\varepsilon_l<0$ ($\Delta<0$) and $\varepsilon_{l+1,m}/\varepsilon_l<0$.

The numerical integration of the guiding center equations makes this picture much more exact.

3. Response of Alpha-Particle Orbits on Transverse Field Change

Below there are shown the alpha-particle (W=3.5 MeV) trajectories which are obtained with the numerical integration of the guiding center equations

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t}=V_{\parallel}\frac{\boldsymbol{B}}{B}+\frac{M_j(2V_{\parallel}^2+V_{\perp}^2)}{2e_jB^3}[\boldsymbol{B}\nabla B],$$

$$\frac{\mathrm{d}W}{\mathrm{d}t}=0,\qquad\frac{\mathrm{d}\mu}{\mathrm{d}t}=0,$$

where all denotions are standard. For our study B_0=12 T; the magnetic field is taken in the form $\boldsymbol{B}=\nabla\Phi$, the values of $\varepsilon_{n,m}$ are taken to describe the configurations of FFHR reference and compact cases [1,5]. The trajectories are shown on the background of the magnetic force line footprints which form closed magnetic surfaces.

FFHR Reference. Under the effect of $B_{\perp}$ the modulation of the magnetic field along the force line ($B(\varphi)$) can be changed (Fig. 1). In the case $\Delta<0$ the modulation of $B(\varphi)$ [Fig 1.c] can be favourable to reduce the radial drift of the trapped particles [7] and the passing particles as we have shown in Section 2. As we can see (Fig. 2) the deviation of the particle from the initial magnetic surface in the case $\Delta<0$ is smaller than in the cases $\Delta=0$ and $\Delta>0$.

FFHR Compact System. The more compact systems are of great interest, for example, FFHR with the parameters R=13.2 m, a_h=3.3 m, l=3, m=12 [1], where the condition of the force-free-like helical windings γ=1 is

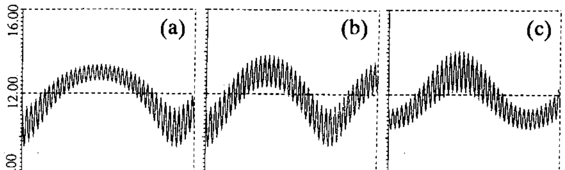

Fig. 1 Magnetic field modulation along the force line in the FFHR reference case under $B_{\perp}/B_0$=-0.003 (a), 0.0 (b), 0.005 (c).

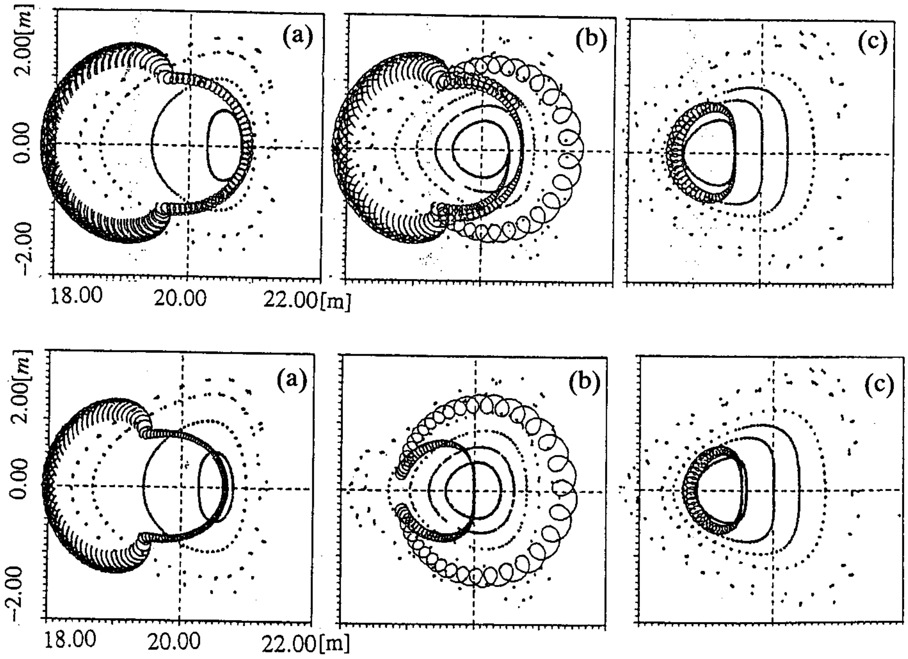

Fig. 2 Projections of alpha-particle trajectories on the meridional cross-section in the FFHR reference case under $B_\perp/B_0=-0.003$ (a), 0.0 (b), 0.005 (c) for $V_\parallel/V=-0.3$ and the starting point near the equatorial plane from the weaker toroidal field side (top) and near the vertical axis passing through the magnetic axis and crossing the initial magnetic surface (down).

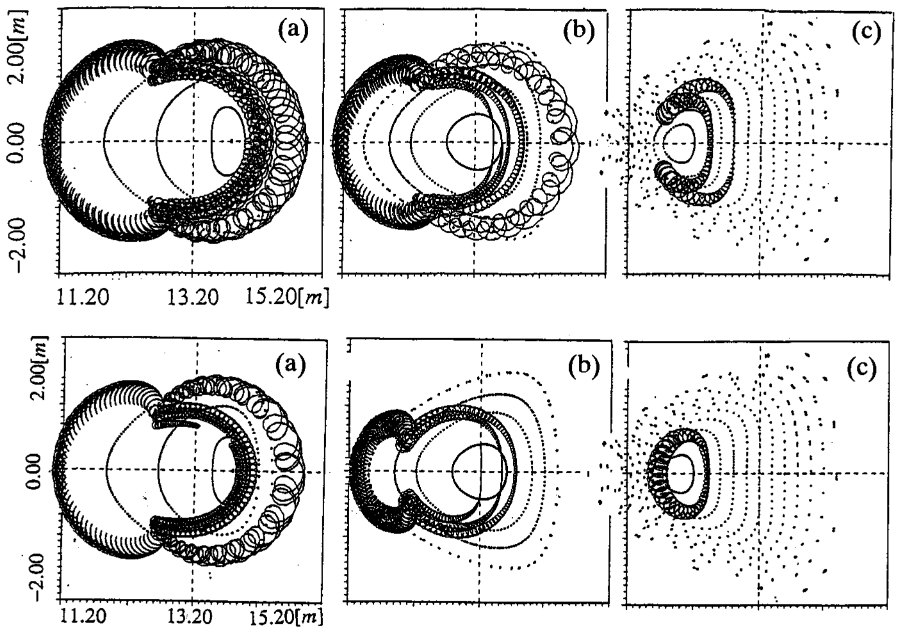

Fig. 3 The same as Fig. 2 but in the FFHR compact case.

satisfied also. However, the increase in the toroidicity may be the reason of the enhanced radial drift of the high energy particles. Here we have shown the possibility to reduce considerably the deviation of the alpha-particle orbits from the initial magnetic surfaces in the case $\Delta<0$ (Fig. 3). In such configuration the difference between passing particles with $V_\parallel<0$ and $V_\parallel>0$ is small. Trajectories of particles launched from the same initial

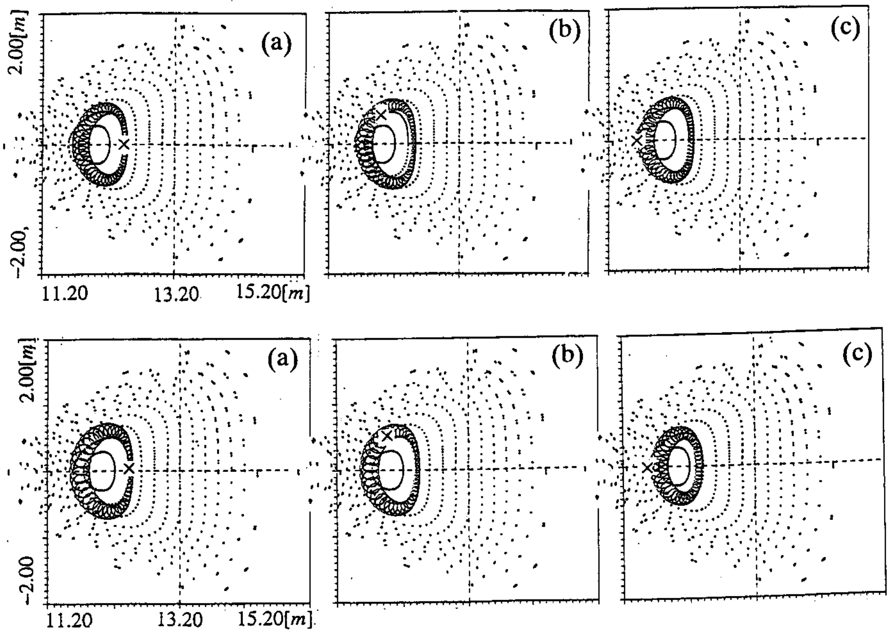

Fig. 4 Projections of alpha-particle trajectories on the meridional cross section in the FFHR compact case under $B_\perp/B_0=0.005$ for three starting points at $V_{\parallel}/V=0.9$ (top) and $V_{\parallel}/V=-0.9$ (down).

positions [Fig.4 (a)-(c)], the starting points marked with crosses", are the similar. This is the feature of the configuration favourable for the confinement properties [6].

4. Summary

1) With the use of the externally applied transverse magnetic field it is possible to decrease the deviation of alpha-particles from the initial magnetic surface in the case of the inner shift of the magnetic axis in $l=3$ Force Free Helical Reactor.
2) The negatively and positively passing particle orbits are not distinguished one from other that is the feature of the configuration with the reduced effect of the toroidal field gradient on the particle confinement.
3) Effects mentioned above take place in $l=3$ helical systems with the coil aspect ratio $R/a_h=7$ and 4. The possibility to reduce the deviation of the alpha-particles is rather important in the compact system.
4) Here the principal possibility of the improvement of alpha-particle confinement is shown, the loss cone analysis is under study now.

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