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INFLUENCE OF FLUX SURFACE NONCIRCULARITY ON THE ALPHA PARTICLE CONFINEMENT IN JET

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Introduction

The present paper investigates the effect of flux surface noncircularity on the confinement of fast ions in JET-like tokamak plasmas. This investigation is important for extending the 3D Fokker-Planck simulation of alpha particle behaviour in TFTR [1-5] to also include tokamaks with noncircular flux surfaces.

The previous analytical model of a TFTR-like tokamak magnetic configuration [1,4,5] is rendered applicable for a JET-like one by taking into account the flux surface elongation and the triangularity $\Lambda(r)$ with r denoting the flux surface radius at the midplane. The influence of ellipticity and triangularity on the fast ion confinement domains in the constants-of-motion space is studied for tokamaks with weak TF ripples.

Magnetic field model

We refer here to an axisymmetric magnetic field with the noncircular flux surfaces characterised by

$$R = R_0(r) + r\cos\chi;\; z = k(r) r \sin\chi\left[1 - \Lambda(r)\cos\chi\right]. \tag{1}$$

Here R and z are the spatial variables of the cylindrical coordinate system (R, z, φ), r is the flux surface radius in the equatorial plane $z = 0$, χ the poloidal angle, $k(r)$ the parameter of flux surface elongation and $\Lambda(r)$ the triangularity parameter. $R_0(r) = R_c + \Delta(r)$ is the major radius of a given flux surface with R_c as the major plasma radius and $\Delta(r)$ indicating the Shafranov shift. The corresponding coordinate system is seen in Fig. 1. We note that the effective flux surface elongation, k_{eff}, and the effective triangularity Λ_{eff} are given by

$$k_{eff} = k\sqrt{2}\left(\mathrm{M}(\Lambda) + 2\Lambda^2\right)^{3/2} / \mathrm{M}^2(\Lambda) > k, \quad \Lambda_{eff} = 2\Lambda / \mathrm{M}(\Lambda) < \Lambda, \quad \mathrm{M}(\Lambda) = 1 + \sqrt{1 + 8\Lambda^2}. \tag{2}$$

It can be shown [7] that the flux surface radius r and the poloidal angle χ are related to the flux coordinates $\{\Phi, \vartheta\}$, which determine the toroidal component of the magnetic field ($\mathbf{B}_t = \nabla\Phi \times \nabla\vartheta = \vartheta'(r,\chi)\nabla\Phi \times \nabla\chi$ with $\vartheta'(r,\chi) = \partial\vartheta(r,\chi)/\partial\chi$), by the expressions

$$\frac{d\Phi}{dr} = 2J\frac{d}{dr}\left\{k\left(r_o - \sqrt{r_o^2 - r^2}\right)\left[1 - \frac{\Lambda}{2r}\left(r_o - \sqrt{r_o^2 - r^2}\right)\right]\right\} \tag{3}$$

and

$$\frac{d\vartheta}{d\chi} = \left(1+\frac{l}{2}+\left[d+\frac{\Lambda}{4}(3+m)\right]\cos\chi+\left(d\Lambda-\frac{l}{2}\right)\cos 2\chi+\frac{\Lambda}{4}(1-m)\cos 3\chi\right)\Big/\left((1+\varepsilon\cos\chi)G\right), \quad (4)$$

where $\varepsilon = r/r_0$, $d = dr_0/dr$, $l = d\ln k/d\ln r$, $m = d\ln(k\Lambda)/d\ln r$ and $G = d\Phi/dr/(2J\varepsilon k) \equiv G(\varepsilon, k, \Lambda, d, l, m)$ with J denoting the total poloidal current outside a given flux surface. The profiles of the factor G for k=1.5 and a plasma aspect ratio A=3.17 are shown in Fig. 2, where x is the flux surface radius normalised to the minor plasma radius a, for different triangularities $\Lambda_i = 0.1(i\text{-}1)x^2$. According to Ref. [7] the safety factor q on the flux surface given by Eqs. (1, 2) is determined by

$$q = \left\langle g^{11}\vartheta' \right\rangle/(2JI), \quad g^{11} = \nabla\Phi\nabla\Phi. \quad (5)$$

Taking into account the explicit form of g^{11} and ϑ' this may be expressed as

$$q = q^{(0)}F(k,\varepsilon,\Lambda,d,l,m); \quad q^{(0)} = \left(J\varepsilon^2/I\right)\left(1+k^2\right)/2, \quad (6)$$

where $q^{(0)}$ is the safety factor in the paraxial approximation $\varepsilon = 0$ and for $\Lambda = l = d = m = 0$; $I = I(r)$ is the total toroidal current inside the given flux surface. In this form the factor F describes the contribution of noncircularity to the rotational transform. From Fig. 3 it follows that both triangularity and elongation result in about 2 times an increase of $q(a)$ for JET-like parameters (k=1.5, $\Lambda = 0.3$) when compared to the purely elongated shape in the paraxial approximation. The model flux surfaces for JET discharge No40554 are displayed in Fig. 4. Except of the effect of up-down asymmetry they are seen in excellent agreement with that determined experimentally [8].

Numerical results

It should be pointed out that the product of the factors F and G describes the influence of noncircularity on the banana width [6]

$$\Delta r_{b\,non-circular} = \Delta r_{b\,circular}F(\varepsilon,k,\Lambda,d,l,m)G(\varepsilon,k,\Lambda,d,l,m), \quad (7)$$

where $\Delta r_{b\,circular}$ is the banana width in the case of circular flux surfaces. As evident from Figs. 3 and 4, the flux surface triangularity and elongation result in an essential increase of the radial excursion of alphas in comparison to the case of the circular flux surfaces. The drift orbits of toroidally trapped alpha particles (normalised magnetic moment $\lambda = \mu B_c/E = 1$) and of counter-circulating ones ($\lambda = 0$) having energies $E=E_o$=3.5 *MeV* and E=1.8 *MeV* are presented in Fig. 5 for the 3.45*T*/3.25*MA* JET plasma. It is seen that the typical banana widths are comparable to the plasma radius; therefore one can expect a significant role of orbital effects for alpha particle behaviour in JET. The comparison of confinement domains of 3.5 *MeV* alphas in the cases of k=1.5 and k=1 is presented in Fig. 6 for a fixed safety factor profile. Upper curves correspond to the boundary of the domain for co-moving alphas while the lower curves belong to counter-moving ones. The domain increase and/or the improvement of confinement are clearly demonstrated.

Since the enhanced safety factor and banana width result in the decrease of the Goldston-White-Boozer threshold $\delta_{GWB} = [\varepsilon/(Nq)]^{3/2}(1/\rho_L q') \approx \left(\varepsilon/(Nq)^{3/2}\right)(r/\Delta r_b)$, in noncircular plasmas one may expect also an increase of the stochasticity diffusion domain when compared with the equivalent *I*/*B* discharge in the circular case.

To evaluate the noncircularity effect for the ripple induced collisional transport of fast ions we examine the influence of elongation and triangularity on the toroidally trapped particles being in resonance with the TF ripple perturbations, i.e. on particles satisfying the resonant condition

$$l\omega_b - N\omega_d = 0, \quad l = 0, \pm 1, ... \tag{8}$$

Here ω_b and ω_d are the banana and toroidal precession frequencies and *N* is the toroidal field coil number. Figs. 7 and 8 demonstrate the dependence of the resonance levels with $6 \le l \le 18$ on the flux surface trianuglarity in the $\{\lambda, r_m / a\}$-plane, where r_m is the maximum radial coordinate along the orbit. Figure 7 accords to *k*=1.5 and $\Lambda = 0.5x^2$ while Fig. 8 refers to *k*=1.5 and $\Lambda = 0$. Solid curves in these figures correspond to *E*=1.8 *MeV* and dashed ones to *E*=1.4 *MeV*. As the energy decreases a qualitatively distinctive evolution of resonant levels becomes obvious depending on the triangularity. For triangular flux surfaces $\Lambda = 0.5x^2$ the slowing down results even in pinching toroidally trapped alphas. However in the case $\Lambda = 0$ the resonant bananas with *l*=16 should be lost from the plasma periphery (*r*>0.7*a*) during the slowing down process.

Conclusions

The effects of flux surface noncircularity on the alpha confinement in tokamaks are demonstrated and found to be of great importance both in the ripple induced collisional and stochastic transport of fast particles. This is due to the essential dependence of the toroidal precession and bounce frequency as well as the radial excursions of toroidally trapped particles on the flux surface elongation and triangularity. It should be pointed out that up-down flux surface asymmetry neglected here may also influence the behaviour of alphas.

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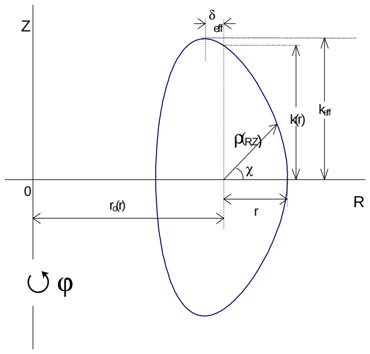

Fig.1 Coordinate system.

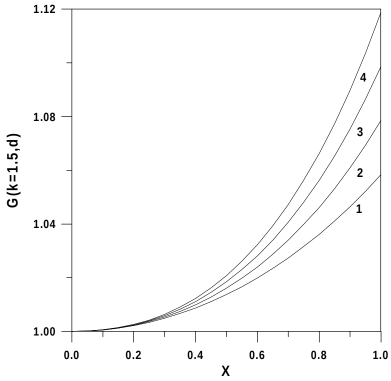

Fig.2 Factor G vs. flux surface radius.

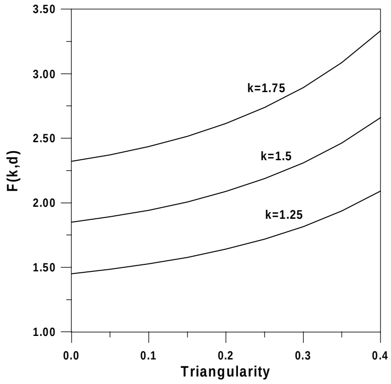

Fig.3 Factor F vs. Λ .

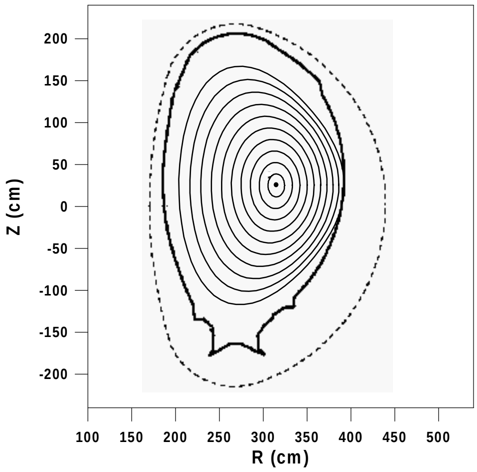

Fig.4 Model flux surfaces.

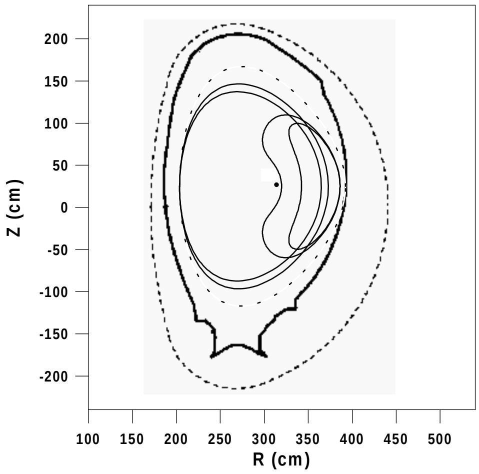

Fig.5 Orbits of 3.5MeV alphas with λ=0, 1, and 1.1and 1.8MeV alphas with λ=0.

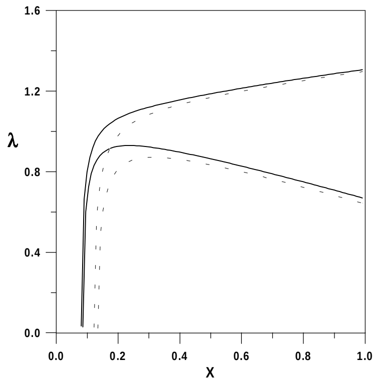

Fig.6 Confinement domains of alphas. Solid line – k=1.5, dashed- k=1, $E=E_o$.

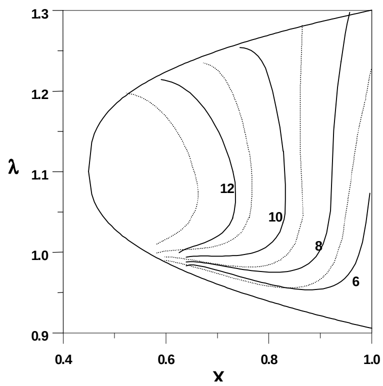

Fig.7 Resonant levels for $\Lambda=0.3x^2$. Solid line-$E=0.5E_o$, dashed-$E=0.4E_o$.

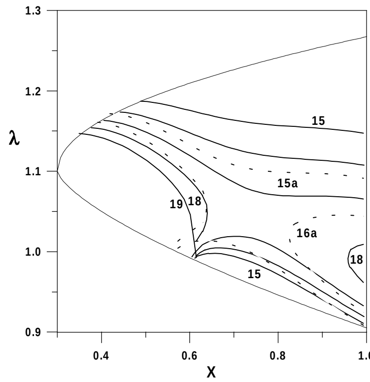

Fig.8 Resonant levels for Λ=0. Solid line-$E=0.5E_o$, dashed-$E=0.4E_o$.