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Neoclassical Transport in Helical Magnetic Axis System in the Low-collisionality ($1/\nu$) Regime

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Abstract

The neoclassical transport in the L=1 helical axis stellarlateor is investigated. The effective toroidal curvature term ε_T defined as the sum of usual toroidal curvature and one of the nearest satellite harmonics of helical field, determines the confinement properties of localized trapped particle. The reduced ε_T configuration which is attained in negatively pitch-modulated L=1 torsatron, is found to improve the collisionless and $1/\nu$ regime collisional particle confinement.

1. Introduction

There exist two characteristic transport features appropriate to 3-D helical magnetic axis system. The first is the formation of the largest magnetic islands at the lowest-order rational surfaces because they couple nonlinearly most readily to the nonresonant vacuum magnetic Fourier components, helical magnetic axis field and toroidal field, which cause indirect resonant pressure driven currents at every rational surface and form the islands. The width of island decreases with increasing N (field period number). The second is the role of the effective toroidal curvature term ε_T for localized trapped particles, which determines the collisionless confinement conditions of helically trapped particles. This paper describes the neoclassical transport in the $1/\nu$ collisionality regime for the reduced ε_T configuration of negatively pitch-modulated L=1 helical magnetic axis torsatron with $N = 17$, coil aspect ratio $R/a \sim 8.4$, in which helically trapped particles are completely collisionlessly confined.

2. Effective Toroidal Curvature

The magnetic field strength B in magnetic coordinates (ψ, θ, ϕ) on a given flux surface ψ =const. is represented by its Fourier components $B_{n,m}(\psi)$ as follows,

$$B(\psi,\theta,\phi) = B_{0,0} + 2 \sum_{(n,m)\neq(0,0)} B_{n,m}(\psi)\cos(n\phi - m\theta) .$$

With the rotational transform $\iota / 2\pi << N$ in present case, we can set $\theta \sim N\phi$ [1,2], so that themain L=1 field is rewritten by

$$B \sim B_{0,0}\left[1+\varepsilon_T \cos\theta + \varepsilon_L \cos(N\phi - \theta)+\cdots\right].$$

Here, ε_T is defined as $2(B_{0,1}+B_{N,0})/B_{0,0}$, which gives an effective toroidal curvature term for localized trapped particles rather than usual toroidal curvature term $\varepsilon_t\,(\equiv 2B_{0,-1}/B_{0,0} < 0)$. The term ε_L represent $2B_{N,1}/B_{0,0}$. Defining ε_0 as $2B_{N,0}/B_{0,0}$, we obtain the relation $\varepsilon_T = \varepsilon_t + \varepsilon_0$. These field components for $\alpha^* = -0.2$ (coil winding law $\theta = N\phi + \alpha^* \sin N\phi$) are shown in Fig.1, where ψ is normalized to the outermost flux surface $\psi = 1$. It is noteworthy that ε_0 is positive in the case of $\alpha^* = -0.2$, hence ε_T becomes small. We have reported the collisionles localized trapped particle confinement is improved by this term[2], and the pitch-modulated L=1 system becomes near omnigenous system[3,4].

3. Neoclassical Transport

When we consider the collisional plasma, the $1/\nu$ collisionality regime, where the effective collision frequency ν_{eff} of the helically trapped particles is less than their bounce frequency ω_b and more than the poloidal drift frequency ω_d ($\omega_b > \nu_{eff} > \omega_d$), is characteristic for standard stellarators due to the symmetry break effect of satellite harmonics $B_{N,0}$ and $B_{N,2}$. In this regime, both particle and heat fluxes are proportional to the neoclassical transport surface integral S [5], which depends only on the geometric parameters ε_t, ε_L and ε_{L+i} ($i \neq 0$, satellite harmonics). Figure 2 shows that the transport of the $\alpha^* = -0.2$ case is the smallest of the three α^* cases in the core plasma region($\psi < 0.5$). We can see also the enlargement of radial transport in the outer region ($\psi > 0.5$). This causes mainly by the $\varepsilon_2\,(\equiv 2B_{N,2}/B_{0,0})$ term as described in the next section, but the total loss is insignificant by consideration of the particle density in the outer region.

3. Effects of Satellite Term on the Radial Transport

These facts suggest the important role of ε_T on S even in the presence of collisionality. One of the nearest satellite harmonics of main helical field $B_{N,1}$, $B_{N,0}$ has been reported to contribute to the reduction of ε_T, and lead to the good collisionless confinement of helically trapped particles. On the other hand, the another nearest satellite harmonic $B_{N,2}$ enhances the drift width of helically trapped particles by a factor of ~ 3 in maximum (for deeply trapped particles) compared with that without $B_{N,2}$ harmonic, although it does not give any effect on the confinement conditions of helically trapped particles. This enhancement of drift width suggests the degradation of diffusion coefficient. Figure 3 shows the level contours of $S(\varepsilon_t, \varepsilon_0)$ at $\psi \sim 0.5$ in $\alpha^* = -0.2$ case. Though the parameters ε_t and ε_0 are dependent each other in the real system, these are changed independently with keeping the other Fourier components. It is noticed that the level of the real $\alpha^* = -0.2$ system is near the lowest level of these hypothetical systems, and the region of the low level is along the line $\varepsilon_0 \approx -\varepsilon_t$, which is corresponded to $\varepsilon_T \approx 0$. These results means the role of ε_T on the transport integral even in the presence of collision, and the significantly reduced ε_T, L=1 configuration ($\alpha^* = -0.2$) is near the lowest S region (Fig.3). We evaluate S in three configuration models for $\alpha^* = -0.2$ case. Those are the single helicity model including only ε_t, $\varepsilon_{L(=1)}$ terms, the two helicites model including $\varepsilon_t, \varepsilon_1, \varepsilon_0$ terms, and the multi helicities model including all helical magnetic Fourier terms. In case of the single helicity model, the value of S becomes slightly larger than the multi helicities model. On the contrary, the two helicities model reduces the value significantly. As the results of the research concerning S, the two satellite harmonics of L=1 helical field affect the transport in the $1/\nu$ collisionality regime so that ε_0 makes it decrease by the reduction of ε_T combining with ε_t even in the presence of collision, and ε_2 increase(decrease) when $\varepsilon_2 < 0$ (when $\varepsilon_2 > 0$). Its deviation from the lowest S value is mainly due to ε_2 harmonic and the increasing factor of S is ~ 3.0 on $\psi \sim 0.5$ due to the negative value of ε_2 in case of $\alpha^* = -0.2$ as shown in Fig.4.

4. Conclusion

In conclusion, the reduced ε_T configuration is found to be good radial transport properties even if collisonal regime. The two satellite harmonics of L=l helical field affect the transport in $1/\nu$ collisionality regime so that ε_0 makes it decrease by the reduction of ε_T, combining with ε_t, and ε_2 increase when ε_2 is negative. Our new approach would give rise to the possibility of stellarator design study in a wider parameter domain than quasisymmetry approaches.

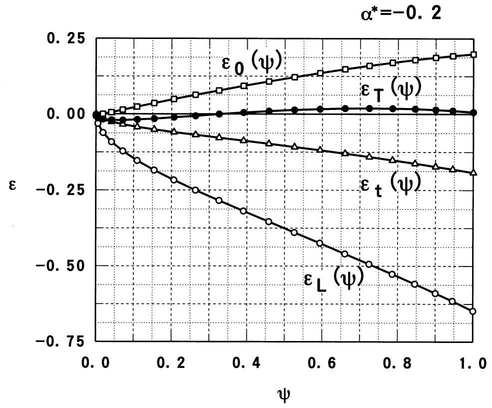

Fig.1 The main field components and the effective Toriodal curvature ε_T.

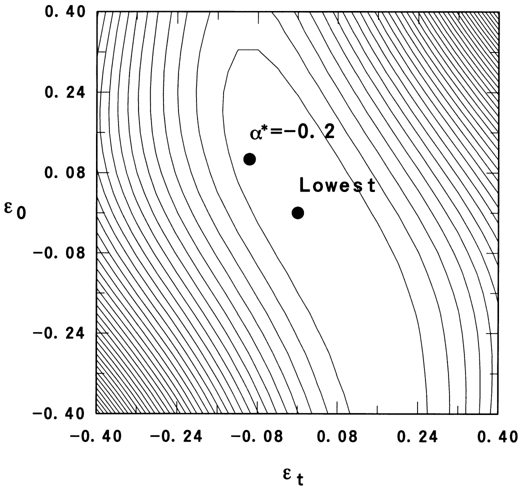

Fig.3 The contours of transport integral S.

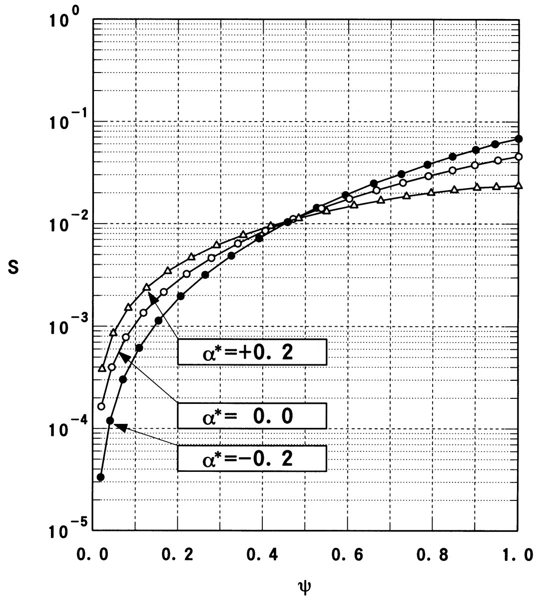

Fig.2 The transport integral S versus ψ. The three pitch-modulation cases are shown.

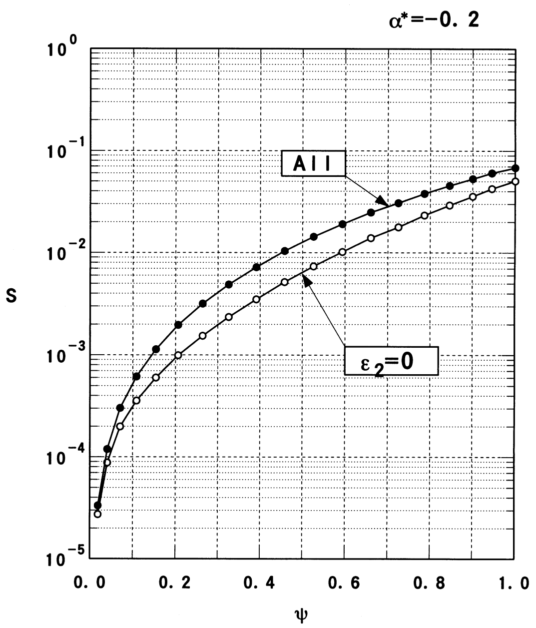

Fig.4 The transport integral S versus ψ. The ε_2 term increase the radial transport.

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