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Various Control Methods of Effective Toroidal Curvature Term for Improving Particle Confinement Properties of L=1 Helical Systems

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Abstract

The trapped particle confinement in the L=1 helical axis stellarator is investigated by the particle orbits tracing and the longitudinal adiabatic invariant J method. The presented systems with reduced effective toroidal curvature term ε_T defined as the sum of usual toroidal curvature and one of the nearest satellite harmonics of helical field, are found to correlate with the omnigenous systems, and the control methods of this curvature are described.

1. Introduction

The L=1 compact helical magnetic axis system has a high magnetic shear, and also a local magnetic well by its modifications[1]. The L=1 torsatron has some advantages over other stellarators; in addition to the simple coil structure and a local magnetic well keeping a positive magnetic shear, the negative pitch modulation ($\alpha^* < 0$) of coil winding law $\theta = N\varphi + \alpha^* \sin N\varphi$ leads to the complete confinement of helically trapped collisionless particles[2], where θ, φ and N ($=17$, coil aspect ratio R/a=2.1m/0.3m=7.0) are the poloidal and toroidal angles and field period number, respectively. This fact suggests that the negatively pitch-modulated L=1 torsatron has the property of quasi-helical symmetry for these trapped particles.

2. Effective Toroidal Curvature and Its Contribution to Particle Confinement

There are two important notices for the helical magnetic axis system to consider good confinement properties. The first is the formation of the largest magnetic islands at the lowest-order rational surfaces because they couple nonlinearly most readily to the non-resonant vacuum magnetic Fourier components, the helical magnetic axis field and toroidal field, which cause indirect resonant pressure driven currents at every rational surface and form the islands [1]. This result requires the large periodic field number *N*. The second is the role of the effective toroidal curvature term ε_T for localized trapped particles defined as the sum of the toroidal field and bumpy field. It determines the collisionless confinement conditions of helically trapped particles [2]. We have reported that this small effective term leads to the good collisionless confinement of helically trapped particles. Then, we have controlled this effective term by some methods. The first method is the pitch modulation of winding law for helical coil, the second is applying the bumpy field by the toroidal field creation coils with various parameters (circular loop coils) [3]. When we consider the collisional plasma, the $1/\nu$ collisionality regime is characteristic for standard stellarators due to the symmetry break effect of satellite harmonics (B_{N0} etc.). In this regime, both particle and heat fluxes are proportional to the neoclassical transport surface integral S [4], and also we found that the negative $\alpha^* = -0.2$ case is near the minimum point in the S-contours [2]. Compared with the bumpy field control methods, the pitch modulation method is easy and effective to control ε_T.

3. Stabilization of Trapped Particle Instability

The charge separation caused by the bad magnetic field curvature drift of the trapped particles results in an $\boldsymbol{E} \times \boldsymbol{B}$ drift flow. This process enhances the amplitude of an initial perturbed density wave and lead to instability. Since the sign of ∇p is negative for radial direction, ∇J must be negative to satisfy the stability condition $\nabla p \nabla J > 0$ (p is a plasma pressure and J is a longitudinal adiabatic invariant.). In our system, the rotational transform per magnetic field period ($\iota / N \sim 0.02$) is small [5], so that we use the following normalized adiabatic invariant J_r defined by

$$J_r = \frac{4B_\varphi}{B_0 a_{ex}} \int_0^{\varphi_c} \frac{u}{B} d\varphi \quad ; \qquad u(\varphi_c) = 0 \qquad ,$$

where B_0 is the field strength at magnetic axis, a_{ex} is the averaged radius for last closed surface, $B_\varphi(\psi)$ is the covariant component of the magnetic field and u is the parallel velocity. The value of J_r is evaluated by giving the fixed ψ and starting particle velocity pitch $\gamma_p \equiv v_{//} / v$. Fig. 1 shows the behavior of $\nabla J_r(\psi, \gamma_p)$ in case of $\alpha^* = -0.2$. This figure suggests that the stability condition is satisfied in the whole region except near the outermost surface $(\psi = 1.0)$.

4. Field Line Hamiltonian

It is well known that the differential equation of a field line trajectory is rewritten to the form of Hamilton's equation of motion by using the magnetic flux coordinates. The magnetic field is equivalent to a one degree of freedom, time-dependent Hamiltonian system. We can also deal with an equivalent time-independent Hamiltonian in two degrees of freedom. When a field is represented by means of a magnetic field line Hamiltonian H_{FL}, the field line can be identified with the phase-space trajectory produced by this Hamiltonian. In case flux surfaces exist, the magnetic field line Hamiltonian is given by

$$H_{FL}(\psi) = \psi_{ex} \int_0^{\psi} \iota\!\!\!-(\psi) d\psi + \psi_{p,0}^d ,$$

where ψ_{ex} is an outermost surface toroidal flux, $\psi_{p,0}^d$ is a poloidal-disk flux enclosed by the magnetic axis, and $\iota\!\!\!-(\psi)$ is a rotational transform. We have evaluated by $\alpha^* = -0.2$ field, and show the H_{FL} (excluding $\psi_{p,0}^d$:constant.) normalized by ψ_{ex} in Fig. 2. And this numerical H_{FL} can reproduce the original filed line. The field-line Hamiltonian contains all the information on the existence of surfaces, island and stochastic regions. We are now studying the L=1 helical field-line Hamiltonian $H_{FL}(\psi, \theta, \varphi)$ which is obtained even if there are no perfect flux surfaces, and investigating the general properties of the L=1 helical filed.

5. Conclusion

The trapped particle confinement is studied by controlling the effective toroidal curvature and the stabilization of micro instabilities by the longitudinal adiabatic invariant J method. As the results, good confinement properties are attained in negatively pitch-modulated cases, especially in case of $\alpha^* = -0.2$, then, the maximum-J configurations are obtained. When we consider the compact system with low aspect ratio and small N value, the various methods described in Sec. 2 would play important roles on ε_T control keeping the compatibility with magnetic well formation.

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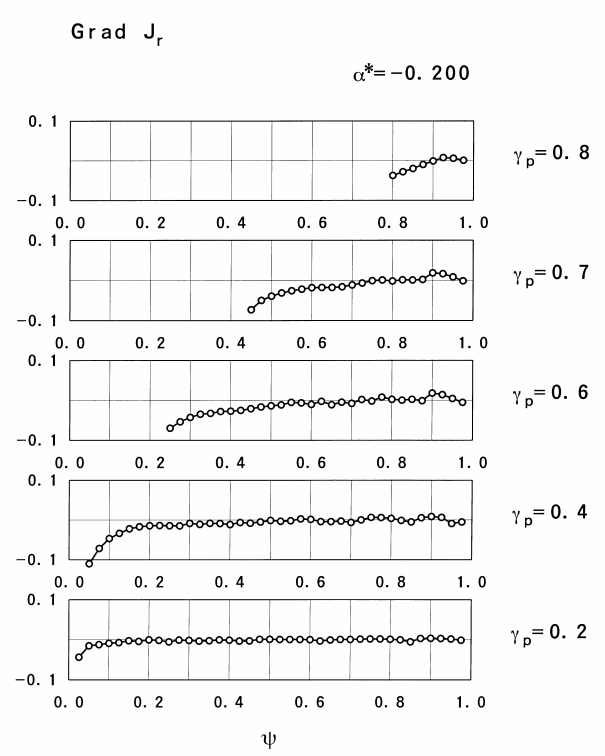

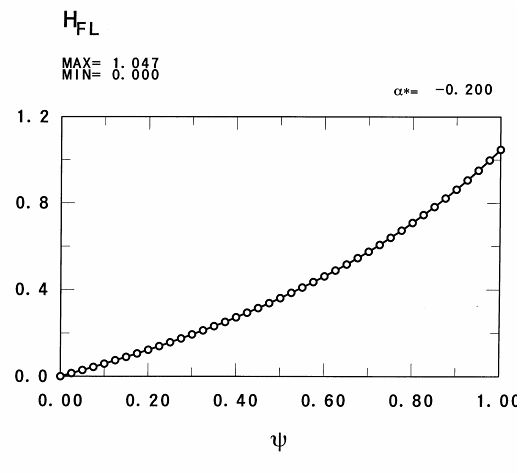

Fig.2 : Field-line Hamiltonian

Fig.1 : Stabilization of Trapped Particle Instability by $\nabla J_r = \partial J_r / \partial \psi < 0$.