L=1 Helical Systems with Improved Particle Confinement Properties

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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, as the results, good confinement properties are attained in negatively pitch-modulated case, and then, the maximum-J configurations are also obtained. 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 and maximum-J systems.

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[2,3], 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. Here, the radial profiles of longitudinal adiabatic invariant J are examined to investigate the trapped particle instability of L=1 torsatron with $\alpha^* < 0$.

2. Effective Toroidal Curvature and Its Contribution to Improved 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. 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 two 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 (circular loop coils)[3]. The topological properties of B and J are examined for negatively pitch-modulated L=1 torsatron, in which helically trapped collisionless particles are completely confined. This favorable collisionless particle confinement can be explained by the topological properties of the configuration which is near the omnigeneity. This means that the L=1 torsatron having the small effective curvature is nearly omnigenous. 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[3]. After summary of our works, we are going to describe the instability due to the trapped particles.

3. Collisionless 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. These trapped particle instabilities can be classified to the two cases, the dissipative and collisionless cases. In this paper, we have treated the collisionless case. In usual, the stability condition of the collisionless trapped particle instability is given by $\nabla p \nabla J > 0$, where p is a plasma pressure and J is a longitudinal adiabatic invariant. Since the sign of ∇p is negative for radial direction, ∇J must be negative to satisfy the above stability condition. In our system, the rotational transform per magnetic field period ($\iota\!\!-/N \sim 0.02$) is small, so that we approximate the invariant J by J_r that is introduced by Cary et. al.[5]. Then we use the following normarlized adiabatic invariant J_r.

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

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 $\gamma_p \equiv v_{//}/v$. While the value of φ_c is not found, we put $J_r = 0$. This is corresponded with passing particle. Fig. 1 shows that an upper figure is the selected J_r from $J_r(\psi, \gamma_p)$ which is a lower figure in case of $\alpha^* = +0.2$. Similarly, Fig.2 and Fig.3 show the $\alpha^* = 0.0$ and $\alpha^* = -0.2$ cases, respectively. These figures suggest that $\alpha^* = -0.2$ case satisfy the stability condition in the whole region except near the outermost surface. The behaviour of passing particles are different from the trapped particles, and they tends to reduce the instability growth. The fraction of the passing particle to the total number are important contribution to suppress the instability, and they are shown in the Table.I. We can see that the fraction of the passing particles becomes large in the $\alpha^* < 0$ cases, and these results are expected to have an advantage for instability in addition to the maximum-J configurations.

4. Conclusion

The trapped particle confinement is studied 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. The presented systems with reduced ε_T are found to correlate with the omnigenous and maximum-J systems. When we consider the compact system with low aspect ratio and small N value, this method would plays important role on ε_T control keeping the compatibility with magnetic well formation.

References

[1] K.H.Saito, M.Aizawa, K.N.Saito, I.Kawakami and S.Shiina. ;
17th IAEA Fusion Energy Conference (Yokohama) IAEA-CN-69/THP1/09 (1998).
[2] M.Aizawa and S.Shiina; Phys. Rev. Lett. **84**, 2638 (2000).
[3] M.Aizawa et.al.; Proc. of the 27-th EPS Conf. on Controlled Fusion and Plasma physics; (Budapest, Hungary, 2000) 1384 (2001).
[4] K.C.Shaing and S.A.Hokin.; Phys. Fluids **26**, 2136 (1983).
[5] J.R. Cary C.L. Hedrick J.S. Tolliver, Phys. Fluids. **31**, 1586(1988).

Fig.1

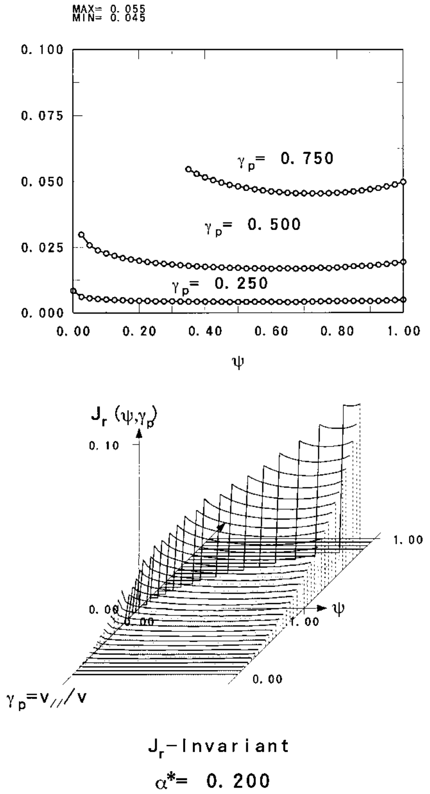

Fig.2

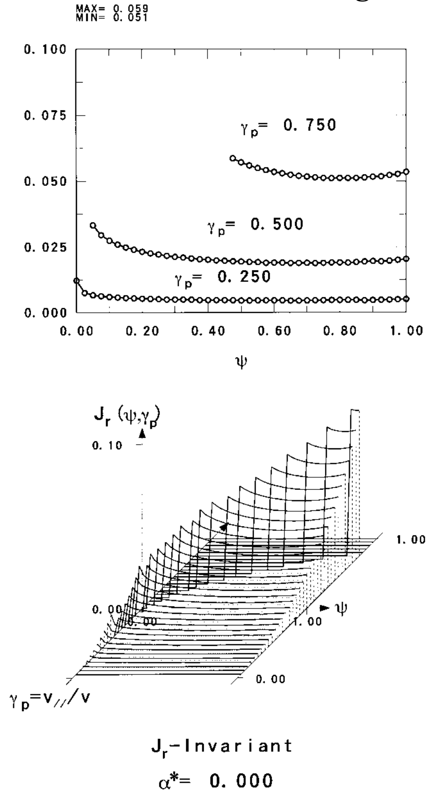

Fig.3

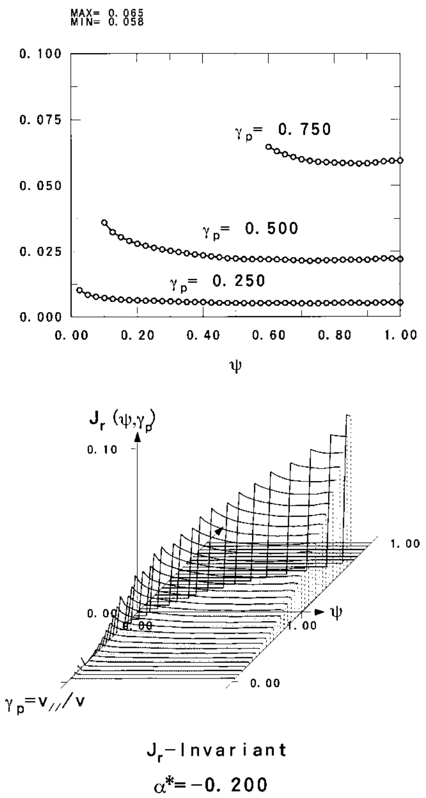

Fig.1,2,3 The longitudinal invariant J_r versus $(\psi,\gamma_p \equiv v_{//}/v)$ for each α^* (+0.2,0.0,-0.2) are shown. The upper part of each figure is picked out of lower part of each figure.

α^*	F_p	F_t	F_h	F_l
+0.4	0.60	0.40	0.24	0.16
+0.2	0.64	0.36	0.21	0.15
0.0	0.68	0.32	0.25	0.07
−0.2	0.71	0.29	0.24	0.05
−0.4	0.75	0.25	0.11	0.14

Table.I Observed Confinement Properties of collisionless particles in pitch-modulated L=1 torsatrons. F_p, F_t, F_h, and F_l are the fraction of passing, trapped, helically trapped (confined) and loss particles, respectively, to the total number.