Application of Effective Toroidal Curvature for Improving Particle Confinement Properties of L=1 Helical Systems

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Abstract

The neoclassical transport in the L=1 helical axis stellarator is investigated. The effective toroidal curvature term $\tilde{\varepsilon}_T$ 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 particles. As one of the methods to control $\tilde{\varepsilon}_T$, the negatively pitch-modulation is applied to the low coil aspect ratio and small periodic number system which stands out a toroidal effect, and we have found our method decrease a neoclassical transport as same as the large aspect ratio case.

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 $\theta$, $\varphi$ 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. We have applied this method to the compact and low coil aspect ratio ($N = 5$, $R/a = 1.0m/0.3m = 3.3$) device.

2. Quantitative Detection of Magnetic Surfaces

The determination of the magnetic surfaces is part of the more general problem of finding the equilibrium state of the plasma. In the helical system, no toroidal plasma current is
required for the existence of magnetic surface against a tokamak, and it is meaningful to study vacuum magnetic surfaces extensively. The usual technique to find magnetic surfaces is the Poincaré plots method shown in the Fig.1 below, and many coils parameters control are necessary for existing surfaces. The important parameters of magnetic surfaces are a magnetic axis and an outermost surface. We have concentrated the automatic decision of these parameters by computers. The position of magnetic axis \( r \) is comparatively easily decided by the iteration method, 
\[
\mathbf{r}^{(i+1)} = F(\mathbf{r}^{(i)})
\]
where \( F \) is the transformation function to approach to magnetic axis. On the other hand, the automatic decision of an outermost surface is hard because of complex pattern recognitions. It is usual that we judge this surface position with the help of our eyes. When we discuss the physical properties about magnetic surfaces, we use the flux coordinates like Boozer’s to clarify the surface quantities. This coordinates can be established from real field properties and requires the information of an outermost surface frequently. Therefore, we have applied the maximum Lyapunov exponent method [3] to the field line integration to definite the boundary position of stochastic behaviour for field line automatically. Fig.1-2 show the Poincaré plots and the corresponding maximum Lyapunov exponents. The points A-D show each same filed line in the two figures. In this case, we have determined the C point as the outermost surface by the value of Lyapunov exponent value within the tolerance level about 0.05-0.1.

3. Effective Toroidal Curvature and Its Contribution to The Low Aspect Ratio Devices

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 non-linearly 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 \( \varepsilon_T \) for localized trapped particles. 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. Compared with the bumpy field coils control methods, the pitch modulation of winding law for helical coil is easy and effective to control \( \varepsilon_T \). When we consider the collisional plasma, the \( 1/v \) collisionality regime is
characteristic for standard stellarators due to the symmetry break effect of satellite harmonics. 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 in case of large $N$ and aspect ratio cases [1]. On the other hand, the transport properties of small $N$ systems are worse than that in the larger $N$ systems. But, the magnetic well control is comparatively easy and device becomes compact. So, we have studied the compact device ($R/a=0.33$ and $N=5$), and the Fourier components of magnetic field strength are shown in Fig.3. The toroidal term $\varepsilon_t$, the bumpy term $\varepsilon_0$, the basic helical term $\varepsilon_L$ and $\varepsilon_T = \varepsilon_t + \varepsilon_0$ are shown. The control of $\varepsilon_T$ by pitch-modulation can be seen in the lower part of Fig.3. The surface integral $S$ is also shown in Fig.4, and the reduction of transport is observed in case of negatively pitch-modulation case.

4. Conclusion

We have studied the L=1 helical systems with improving particle confinement properties, and we have shown the important playing role of the effective toroidal curvature term $\varepsilon_T$ on the particle and heat fluxes. In addition, we have examined the characteristics of L=1 magnetic field itself by the Lyapunov’s exponents method. When we consider the compact system with low aspect ratio and small $N$ value, it is expected that the effective toroidal curvature would play important roles keeping the compatibility with magnetic well formation.

References

Fig.1: The Poincaré plots of L=1 torsatron field. (R/a=7, N=17)

Fig.2: The Lyapunov exponent corresponding to the Poincaré plots (Fig.1).

Fig.3: The L=1 torsatron with no pitch modulation (upper), and with pitch modulation (lower). The main field components and the effective toroidal curvature $\varepsilon_T$ in case of low aspect ratio device are shown. (R/a=3.3, N=5)

The reduction of $\varepsilon_T$ is observed in case of $\alpha^*= -0.2$.

Fig.4: The transport integral $S$ versus normalized flux surface $\psi$ in case of low aspect ratio device which is shown in Fig.3.