Important Role of Effective Toroidal Curvature in L=1 Torsatron

AIZAWA Masamitsu*, YAMAZAKI Hideki1, SAITO Katsuhiko1,
KAWAKAMI Ichiro and SHIINA Shoichi
Atomic Energy Research Institute, College of Science and Technology,
Nihon University, Tokyo 101-0062, Japan
1Graduate School of Quantum Science and Technology,
Nihon University, Tokyo 101-0062, Japan

(Received: 30 September 1997/Accepted: 22 October 1997)

Abstract
Negatively pitch-modulated L=1 torsatron, in which the helically trapped collisionless particles are completely confined, is described. It has been reported that the favorable confinement properties can be explained by the smallness of the effective toroidal curvature εf for the localized helically trapped particles. Here, we show that the L=1 torsatron having the small εf is in magnetic configuration near omnigeneity and leads to good particle confinement.

Keywords:
effective toroidal curvature, L=1 torsatron, helical axis stellarator, negative pitch-modulation, omnigeneity, quasi-helical symmetry

1. Introduction
L=1 compact helical magnetic axis system has a high magnetic shear, and also a local magnetic well by its modifications [1]. 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 (α*<0) of coil winding law θ=Nφ+α*sinNφ leads to the complete confinement of helically trapped collisionless particles[2,3], where θ, φ and N (=17, coil aspect ratio R/a=2.1 m/0.3 m=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 topological properties of magnetic field lines and longitudinal adiabatic invariant J are examined to explain the attractive confinement features of L=1 torsatron with α*<0.

2. Role of Effective Toroidal Curvature on Particle Confinement
The magnetic field strength on a magnetic surface labeled by ψ=const. is represented by Fourier series

$$B(\psi, \theta, \phi)/B_0 \sim 1 - \epsilon_i(\psi)\cos\theta$$
$$+ \sum_{l} \epsilon_{l+1}(\psi)\cos[(L+l)\theta - N\phi],$$

where $B_0$ is the field strength on axis, $\epsilon_{l+1}$ is the satellite harmonics of fundamental helical harmonic $\epsilon_i(i=0)$. For the L=1 torsatron under consideration, relatively large Fourier components are $\epsilon_1$, $\epsilon_i$ and $\epsilon_0 (i=-1)$. In helical magnetic axis system, the rotational transform $N$ associated with the twisting of the surface about the major axis must be added to the usual rotational transform $\epsilon$, so that $\theta \sim \epsilon\phi+N\phi$. With $\epsilon \ll N$, $\theta \sim N\phi$ on any magnetic surface for helically trapped particles. In this

*Corresponding author's e-mail: aizawa@phys.cst.nihon-u.ac.jp

©1998 by The Japan Society of Plasma Science and Nuclear Fusion Research

Aizawa M. et al., Important Role of Effective Toroidal Curvature in $L=1$ Torsatron

B_{\text{min}}$ Contours  

B_{\text{max}}$ Contours  

J' Contours

Fig. 1 $B_{\text{min}}$-contours, $B_{\text{max}}$-contours and $J'$-contours, are shown from the left to the right in the case of $\alpha^*=-0.2$. It is noticed that the drift orbit (25 keV, $v_p/v=0.309$) is superposed on the $J'$-contours and is along the $J'$-contours.

circumstance, the term proportional to $\cos\theta$ is given by the combination of two terms, $\epsilon_1=\epsilon_0$ ($=\epsilon_1$), defined as the effective toroidal curvature term for helically trapped particles. The smallness of $\epsilon_1$ in $L=1$ torsatron having negative $\alpha^*$ is found to lead to the complete collisionless confinement of helically trapped particles[2,3].

3. Topological Properties of Magnetic Field and Invariant $J$

In order to understand physically the role of $\epsilon_1$ on the favorable collisionless particle confinement, the topological properties of magnetic field lines and longitudinal adiabatic invariant $J$ are examined. $J$-contours are directly evaluated by the following normalized invariants based on the longitudinal adiabatic invariants[4].

$$J_1 = \frac{4B_x}{B_0\alpha_{z\text{ax}}} \int_0^{\psi} \frac{u}{B} d\varphi + u(\varphi_c) = 0$$

$$J_2 = +\frac{2\pi}{N} \int_0^\psi \tau d\psi + \frac{B_x}{B_0\alpha_{z\text{ax}}} \int_0^{\frac{\psi}{N}} \frac{u}{B} d\varphi ,$$

where $B_0$ is the field strength at magnetic axis, $\alpha_{z\text{ax}}$ is the averaged radius for last closed surface, $B_x(\psi)$ is the covariant component of the magnetic field and $u$ is the parallel velocity. Figure 1 shows the contours of the local magnetic minima $B_{\text{min}}$, maxima $B_{\text{max}}$ and $J$ in the case of $\alpha^*=-0.2$ having the smallest value $\epsilon_1$. As expected, these contours should align with magnetic flux contours to vanish the bounce averaged cross-flux-surface drift, or to achieve the omniogeneity systems[5] with good particle trajectories. The observed favourable collisionless particle confinement can be understood in terms of the creation of poloidally closed contours of $B_{\text{min}}$, $B_{\text{max}}$ and $J$. The condition of $B_{\text{min}}$-contours is condition so that the deeply trapped particles are omnigenous, and the condition of $B_{\text{max}}$-contours ensures both omnigenous of the marginally trapped particles and elimination of the chaotic transition particles. Recently, it is shown from the form of the bounce action that the angular separation along a magnetic field line of any two contours of the same value of $B$ is constant on a magnetic surface[6]. Figure 2 shows the contours of the magnetic field strength in coordinates $(\theta, \zeta = N\psi - \theta)$ on a surface $\psi=0.5$ in the case of $\alpha^*=-0.2$. This field

| B | Contours

Fig. 2 $|B|$ $(\theta, N\psi - \theta)$-contours on the flux surface $\psi=0.5$ (normalized by the last closed surface). Two thick solid lines mean two contours having the same value of $|B|$.  

512
is found to be nearly quasi-helical by the fact that the contours are near the lines of constant $\zeta$ and to be near omnigenous.

4. Conclusion

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 favourable collisionless particle confinement can be explained by the topological properties of the configuration which is near the omnigenity. This means that the $L=1$ torsatron having the small effective curvature is nearly omnigenous.

References