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Important Role of Effective Toroidal Curvature in $L = 1$ Torsatron

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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 ε_T for the localized helically trapped particles. Here, we show that the $L=1$ torsatron having the small ε_T 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 ($\alpha^* < 0$) 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 $R/a = 2.1$ 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 $\alpha^* < 0$.

2. Role of Effective Toroidal Curvature on Particle Confinement

The magnetic field strength on a magnetic surface labeled by $\psi = $const. is represented by Fourier series

$$B(\psi, \theta, \varphi)/B_0 \sim 1 - \varepsilon_t(\psi)\cos\theta + \sum_i \varepsilon_{L+i}(\psi)\cos\{(L+i)\theta - N\varphi\},$$

where B_0 is the field strength on axis, ε_{L+i} is the satellite harmonics of fundamental helical harmonic $\varepsilon_L (i=0)$. For the $L=1$ torsatron under consideration, relatively large Fourier components are ε_L, ε_t and ε_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 ι, so that $\theta \sim \iota\varphi + N\varphi$. With $\iota \ll N$, $\theta \sim N\varphi$ on any magnetic surface for helically trapped particles. In this

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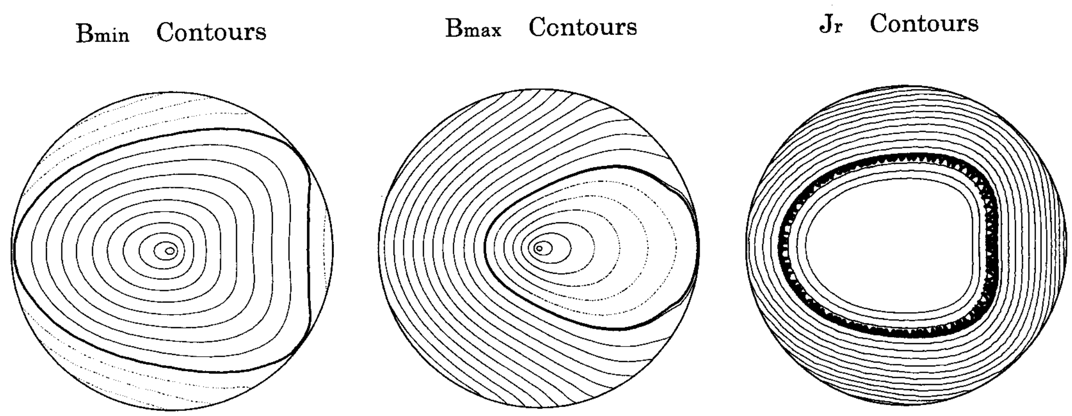

Fig. 1 B_{min}-contours, B_{max}-contours and J_r-contours, are shown from the left to the right in the case of $\alpha^* = -0.2$. It is noticed that the drift orbit (25 KeV, $v_{\parallel}/v = 0.309$) is superposed on the J_r-contours and is along the J_r-contours.

circumstance, the term proportional to cosθ is given by the combination of two terms, $\varepsilon_t - \varepsilon_0$ ($\equiv \varepsilon_T$), defined as the effective toroidal curvature term for helically trapped particles. The smallness of ε_T in $L=1$ torsatron having negative α^* 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 ε_T 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].

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

$$J_+ = + \frac{2\pi}{N} \int_0^{\psi} \iota \mathrm{d}\psi + \frac{B_\varphi}{B_0 a_{ex}} \int_0^{\frac{2\pi}{N}} \frac{u}{B} \mathrm{d}\varphi \,,$$

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. Figure 1 shows the contours of the local magnetic minima B_{min}, maxima B_{max} and J in the case of $\alpha^* = -0.2$ having the smallest value ε_T. As expected, these counters should align with magnetic flux contours to vanish the bounce averaged cross-flux-surface drift, or to achieve the omnigeneity 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_{min}, B_{max} and J. The condition of B_{min}-counters is condition so that the deeply trapped particles are omnigenous, and the condition of B_{max}-contours ensures both omnigeneity 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 (θ, $\zeta \equiv N\varphi - \theta$) on a surface $\psi = 0.5$ in the case of $\alpha^* = -0.2$. This field

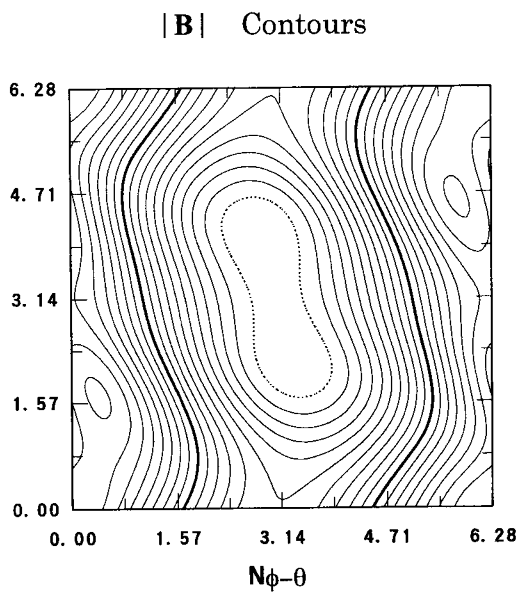

Fig. 2 $|B\ (\theta,\ N\varphi-\theta)|$-contours on the flux surface $\psi = 0.5$ (normalized by the last closed surface). Two thick solid lines mean two contours having the same value of $|B|$.

is found to be nearly quasi-helical by the fact that the contours are near the lines of constant ζ 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 colisionless particles are completely confined. This favourable 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.

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