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Study of Energetic Particle Confinements in Strongly Inward Shifted Configurations of LHD

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Abstract

Energetic particle confinement in strongly inward shifted configurations of the Large Helical Device (LHD) is studied using Monte Carlo simulation code. Collisionless alpha-particle confinement is investigated assuming reactor sized LHD based on three typical configurations with different magnetic axis positions in the major radius. It is found that the inward shift of magnetic axis improves the alpha-particle confinement strongly and a sufficient confinement of alpha-particle for fusion reactor is obtained in the strongly inward shifted configuration. The flexibility of the LHD magnetic configuration is demonstrated for studies of energetic particle confinements in a helical fusion reactor.

Keywords:

LHD, energetic particle, alpha particle, helical reactor

1. Introduction

Confinement of energetic particle is an important issue for fusion reactor. The alpha-particle has about 20 % of thermonuclear power and the additional heating by NBI and/or ICRF heating generates energetic particle. A sufficient confinement of energetic particle is required for an efficient fusion reactor.

The behaviors of trapped particles in helical ripples are complicated and would enhance the radial transport in heliotrons, because of three dimensional magnetic configuration. Thus the confinement of energetic particle is a key issue for a future reactor based on the helical system. To study the energetic particle confinement experimentally NBI (P_{NBI} = 10 MW, E_{b} = 150 keV) and ICRF (P_{ICRF} = 2 MW, f = 34.75 MHz) heating experiments have been performed in the Large Helical Device (LHD; l=2, m=10 heliotron) [1-4] and the confinement of energetic ions (up to 400 keV of tail ion by ICRF heating and 150 keV of tangentially injected beam ion by NBI heating) have been measured.

On the other hand, the LHD can be flexible about the configuration and we can move the plasma horizontally to shift the magnetic axis position inward or outward relative to the center of helical coils by controlling the axisymmetric poloidal fields. The shift of the magnetic axis position alters characteristics of the ripple-induced transport and, especially, a strong inward shift reduces the ripple-induced transport to the comparable level of "advanced stellarators" [5, 6].

In this paper we study the energetic ion confinements in strongly inward shifted configurations of LHD. Collisionless alpha-particle confinements are investigated assuming reactor sized devices base on three typical configuration of LHD with different magnetic axis position in the major radius; R_{ax} = 3.75 m

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(standard heliotron configuration), 3.6 m (σ-optimized configuration), 3.53 m (neoclassical-tarnsport-optimized configuration). The optimum axis position for the ripple-induced transport is 3.53 m and a good confinement of energetic particle is expected. In this study we assume a magnetic configuration in a low beta limit as a first step to show a flexibility of LHD magnetic configuration.

2. Magnetic Configurations of Strongly Inward Shifted LHD

The shift of the magnetic axis alters the magnetic field configuration in flux coordinates. Figure 1 shows the Fourier spectrum of the magnetic field as a function of the plasma radius (left) and the contour plots of mod-*B* (right) on the flux surface at r/a=0.5. Three typical cases are plotted with different magnetic axis position; R_{ax} = 3.75 m (top), 3.6 m (middle), 3.53 m (bottom), where (m,n) represents the Fourier components of the magnetic field, $B_{m,n}$, with the poloidal mode number, m, and the toroidal mode number, n, in the Boozer coordinates.

In the R_{ax} = 3.75 m case there are two dominant components, the main helical curvature term, $B_{2,10}$, and the toroidal curvature term, $B_{1,0}$, and an additional small

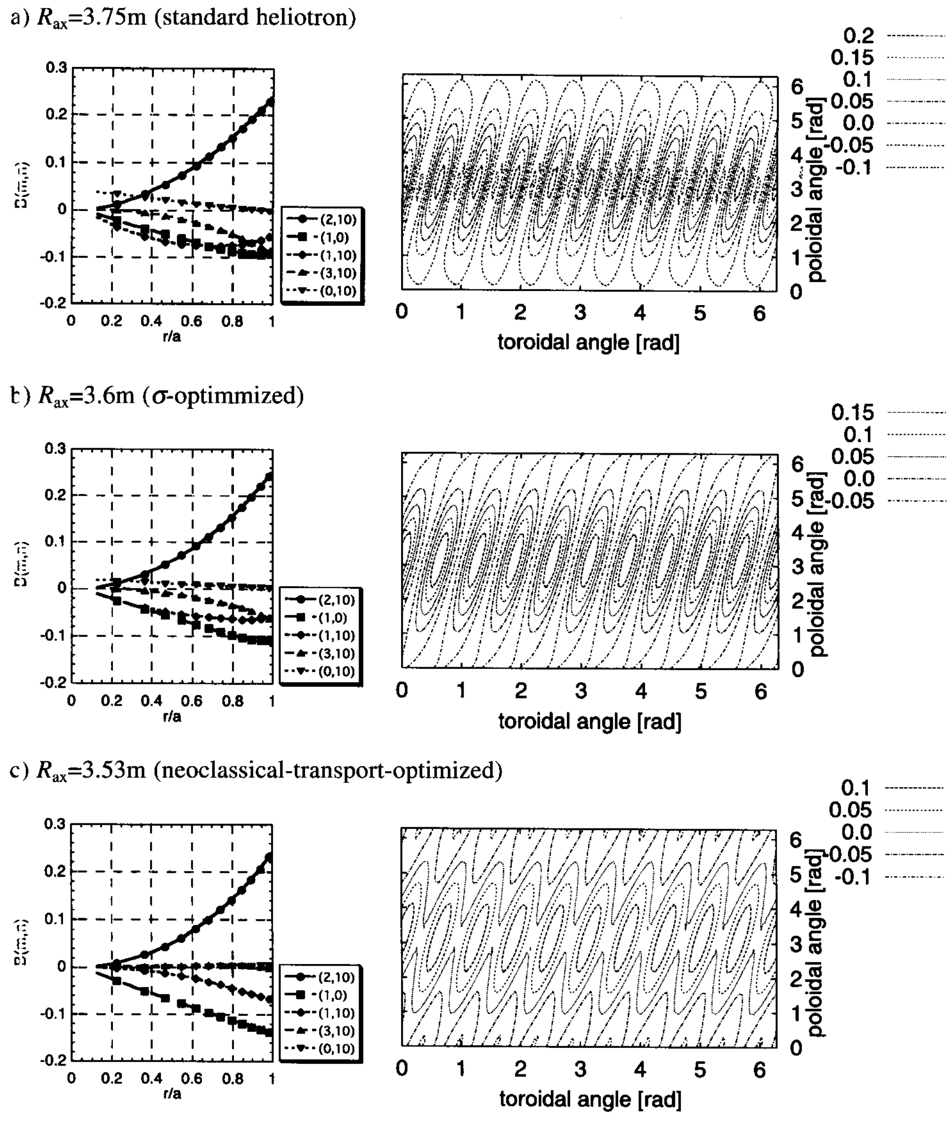

Fig. 1 Radial profiles of the Fourier spectrum of the magnetic field as a function of the plasma radius (left) and the variation of magnetic field strength along the magnetic field line (right) in three typical configurations; R_{ax} = 3.75 m (top), 3.6 m (middle), and 3.53 m (bottom).

component $B_{1,10}$, which is a side band term of $B_{2,10}$. The contour plots of mod-B shows the helical modulation by $B_{2,10}$ and the poloidal modulation by $B_{1,0}$. The maximum point of B located at the inner major radius side (poloidal angle = π) and minimum point appears at the outer side (poloidal angle = 0). This is a typical behavior of the magnetic field variation in a heliotron device.

Shifting the magnetic axis inwards to R_{ax} = 3.6 m, two side bands of the main helical curvature term, $B_{1,10}$ and $B_{3,10}$, increase and their amplitudes become comparable to that of $B_{1,0}$. Then the contour profile changes and no clear minimum point could be seen. This indicates that the R_{ax} = 3.6 m configuration conforms to a "σ-optimized" field [7], where the neoclassical transport is significantly improved relative to a standard heliotron configuration.

A further inward shift of the magnetic axis increases the toroidal mirror term, $B_{0,10}$, in addition to the two side band terms for the R_{ax} = 3.53 m case. The contour plots shows that both of the maximum and minimum points located at the inner side of the major radius (poloidal angle = π). A similar contour profile also seen in optimized helias configurations, in which an important role of the toroidal mirror term has been discussed [8]. In analogy, the increase in the two side bands of the main helical term and the toroidal mirror term improve the neoclassical transport in the R_{ax} = 3.53 m configuration beyond that of the "σ-optimized" (R_{ax} = 3.6 m) case.

In the followig section we study the alpha-particle confinement extending to the reactor size device based on the three typical configuration of LHD; the standard heliotron configuration (SH: R_{ax} = 3.75 m), the σ-optimized configuration (SO: R_{ax} = 3.6 m) and the neoclassical transport optimized configuration (NTO: R_{ax} = 3.53 m).

3. Confinements of Energetic Particles

Assuming reactor size device (plasma volume: 1000 m^3 and magnetic field at plasma center: 5 T) based on three typical configuration of LHD (SH, SO, NTO) we study the collisionless alpha-particle (energy: 3.4 MeV) confinemen. A good confinement of alpha-particle is required for a time longer than the energy slowing down time, τ_{Es}~0.1 s ($n = 1.0\times10^{20}\ m^{-3}$, T_e = 10 keV). Alpha-particles which get lost after the slowing-down time do no contribute to the energetic particle loss.

Figure 2 shows typical orbits of helically trapped alpha-particles in the three configurations of reactor sized LHD; SH (left), SO (center), and NTO (right). We plot the toroidal projection of the orbits in the Boozer coordinates. The co-centric circles corresponds magnetic surfaces and the outermost one is the last closed magnetic surface (r/a=1). We can see the deviation of the trapped particle orbit from the magnetic surfaces reduced by shifting the magnetic axis position inwardly. The deviation is almost disappears in the NTO case.

Next we follow the orbits of alpha-particles starting from the flux surface r/a=0.25. The test particles are randomly distributed in the poloidal and toroidal directions, and also in the pitch angles. The equations of guiding center drift motions are solved in the Boozer coordinates evaluated by NEWBOZ code (See Appendix of ref. [9]) base d on the obtained MHD equilibrium.

The radial distribution of alpha-particles is evaluated in the three configurations of reactor sized

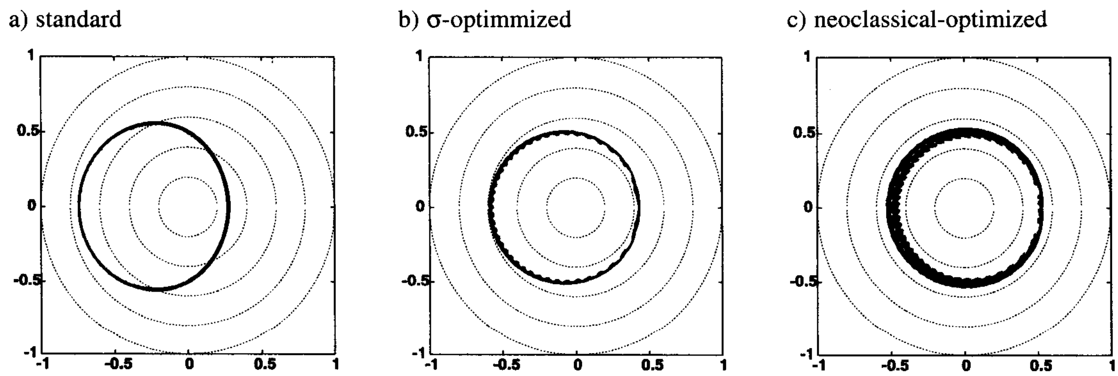

Fig. 2 Typical orbit of a helically trapped alpha-particle (pitch angle: 0.47π) in the three configurations of reactor sized LHD based on the standar heliotron (left), the σ-optimized (center), and the neoclassical transport optimized (right) configurations.

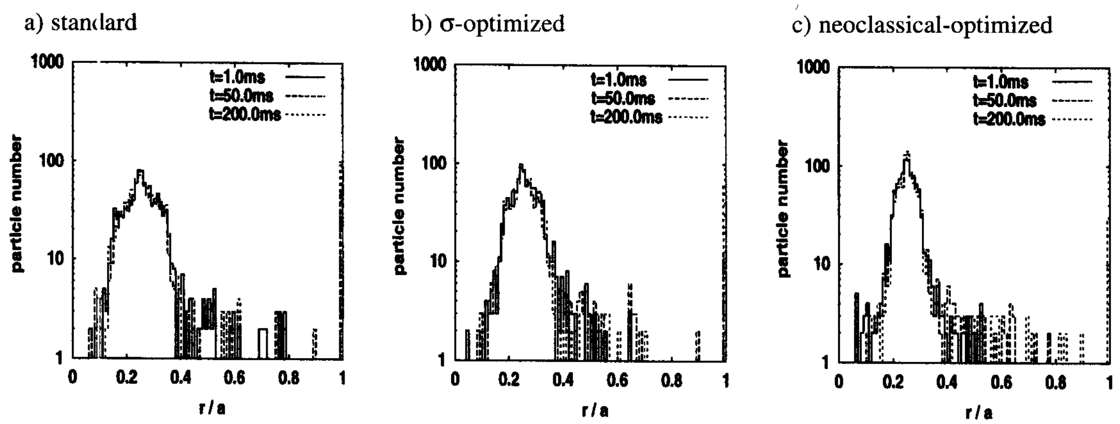

Fig. 3 Radial distribution of alpha-particles started on the flux surface of r/a=0.25 at t=0 in the three configurations of reactor sized LHD based on the standar heliotron (left), the σ-optimized (center), and the neoclassical-transport-optimized (right) configurations.

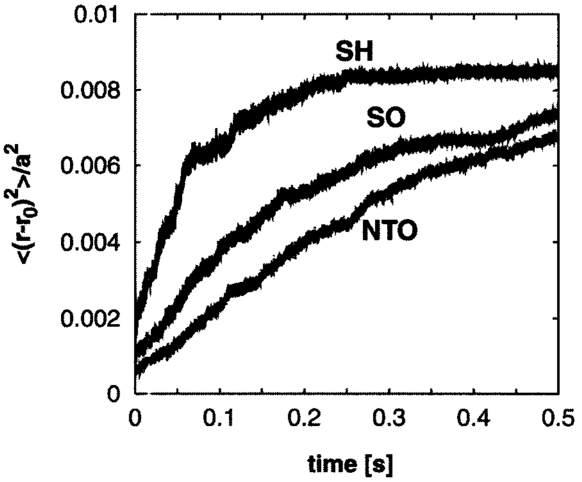

Fig. 4 Time development of averaged mean square of radial displacement of alpha-particles in the three configurations of reactor sized LHD.

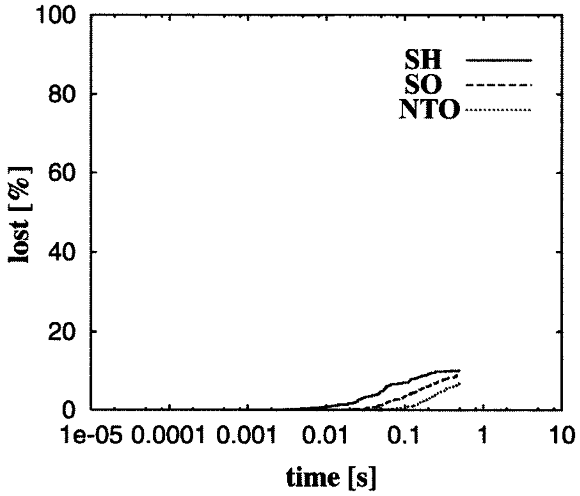

Fig. 5 Time development of alpha-particle loss rates in the three configurations of reactor sized LHD.

LHD; SH (left), SO (center), and NTO (right). We can see the sharp peak near r/a=0.25 in the three cases due to the distribution of passing particles, that stay almost at the starting magnetic flux surface. Then the broader radial distribution can be seen due to the distribution of the deeply trapped particles, that have a relatively wide radial orbit size but draw almost same orbit. Because of larger radial orbit size of trapped particle in the SH configuration (see Fig. 2) a broader radial distribution can be seen in the SH case. The width of distribution becomes a narrower one in the NTO case.

The orbits of passing and deeply trapped particles are stable and do not contribute to the particle loss. On the other hand, there exists a particle so called "transition particle", which experiences both of the helically trapped particle and passing particle depending on location on the flux surface. The transition of particle orbit lead to a change of radial position and makes radial diffusion. Behavior of those transition particles is very important in the helical reactor. The observed radial diffusion and loss of alpha-particle is due to the transition particle.

Figure 4 shows the time development of averaged mean square of radial displacement of alpha-particles from initial point. The mean square value increases in time and the largest increase can be seen in the SH case and the saturation of the increase also can be seen due to the significant loss of alpha-particle. The increment is much smaller in the NTO case.

Finally we evaluate the collisionless orbit loss of alpha-particles as a function of time in Fig. 5. It is found that there is no loss before 0.01s but the loss of alpha-particles increases after 0.01s in the SH case. However the loss starts after the energy slowing down time (~0.1s) of a typical reactor plasma in the NTO case. Thus a sufficient confinement of alpha-particle is obtained in the NTO configuration for a helical reactor.

4. Conclusions

We have studied the confinements of energetic particles in strongly inward shifted configurations of LHD using Monte Carlo simulation code. Collisionless alpha-particle confinements have been calculated assuming reactor sized devices base on three typical configuration of LHD; R_{ax} = 3.75 m (standard heliotron), 3.6 m (σ-optimized), 3.53 m (neoclassical-tarnsport-optimized). It is found that the loss rate of energetic particles is significantly reduced in the neoclassical-tarnsport-optimized configuration and a good confinement of alpha-particle is obtained for a time longer than the energy slowing down time. The obtained results have shown the foundamental property of energetic particle confinement in which the deflection time is much longer than the slowing-down time. As a result we have demonstrated the flexibility of the magnetic configuration of LHD and shown the capability of the energetic particle confinement experiment using a reactor extensible configuration in LHD.

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