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Neoclassical Transport Optimization of LHD

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Abstract. Neoclassical transport is studied for LHD configurations in which the magnetic axis has been shifted radially by determining the mono-energetic transport coefficient and the effective helical ripple. With respect to the transport in the long mean free path collisionality region - the so called $1/\nu$ transport -, the optimum configuration is found when the magnetic axis has a major radius of 3.53m, which is 0.22m inward shifted from the "standard" configuration of LHD. In the optimized case, the effective helical ripple is very small, remaining below 2% inside 4/5 of the plasma radius. This indicates that a strong inward shift of the magnetic axis in the LHD can diminish the neoclassical transport to a level typical of so-called "advanced stellarators".

Keywords: neoclassical transport, optimization, heliotron, LHD, Monte Carlo method

The existence of the $1/\nu$ regime, in which the neoclassical transport coefficients are inversely proportional to the collision frequency, increases the neoclassical particle and heat transport in non-axisymmetric devices to levels far above those of axisymmetric tokamaks in the fusion-relevant long-mean-free-path (*lmfp*) regime. Thus, the reduction of neoclassical transport is one of the key issues for any future fusion reactor based on a non-axisymmetric configuration. Recently, efforts have been undertaken to find configurations having both significantly reduced neoclassical transport and good MHD stability, so-called "advanced stellarators".

The Large Helical Device (LHD)[1] has been constructed as a standard heliotron type device but has a great deal of configurational flexibility. For example, it is possible to shift the plasma horizontally, moving the magnetic axis position inward or outward relative to the center of the helical coils by altering the axisymmetric poloidal fields. Many configurations were investigated while designing the LHD and it was found that as the magnetic axis is shifted inwards (outwards), the properties of the collisionless trapped-particle confinement and neoclassical transport are improved (deteriorated)[2][3], while ideal MHD stability is worsened (improved)[4].

Ultimately, the design team of LHD proposed a configuration called the "standard" configuration, with the magnetic axis at a major radius of $R_{ax} = 3.75$m. This configuration satisfies the requirements for good plasma performance, i.e. good particle confinement, high plasma beta, and the presence of a divertor. However, a relatively large effective helical ripple exists in this configuration and further optimization of neoclassical transport is possible if we exclude the ideal MHD stability condition.

LHD experiments were started in 1998 and have shown good plasma performance[5]–[7]. The experiments have been performed not only in the standard configuration ($R_{ax} = 3.75$m) but also in the "inward shifted" configuration ($R_{ax} = 3.6$m), in which the ideal MHD stability analysis predicts instability. Interestingly, however, no degradation of the plasma confinement has been observed in the experimental plasma of the $R_{ax} = 3.6$m configuration and, furthermore, the energy confinement is found to be better than that of the $R_{ax} = 3.75$m case[8]. The similar improvement of plasma confinement in the inward shifted configuration has also observed in the CHS[9]. These facts suggest that the MHD stability problem is not a severe one for plasma confinement in heliotron and makes it reasonable to consider shifting the magnetic axis further inwards where further improvement of the neoclassical transport can be expected in LHD. Actually, LHD can be operated in the configuration shifting the magnetic axis from 3.45m to 4.05m.

In this paper we study the neoclassical transport in strongly inward-shifted configurations of the LHD and find a neoclassical-transport-optimized configuration by evaluating a mono-energetic neoclassical transport coefficient. In order to compare the neoclassical transport properties of this optimized configuration with those of "advanced stellarators", an effective helical ripple, ε_{eff}, is also evaluated from the transport coefficients obtained. The neoclassical transport coefficient in the $1/\nu$ regime is proportional to $\varepsilon_{eff}^{3/2}$ and the neoclassical transport in the *lmfp* regime can be easily estimated by the value of ε_{eff}.

We evaluate a mono-energetic local transport coefficient using DCOM (Diffusion COefficient calculator by Monte-Carlo method)[10] in which test particle orbits are followed solving the equations of motion in Boozer coordinates and the transport coefficient is evaluated statistically from the mean square displacement of the particles. Thus, DCOM can be applicable to the local neoclassical transport analysis and the global simulation code, e.g. GNET[11], should be applied in the case where the large orbit size of trapped particle plays an important role.

The diffusion coefficients are evaluated for configurations with different magnetic axis positions, R_{ax}, at three different normalized plasma radii; r/a = 0.25, 0.5, and 0.75. In this study we assume electrons as test particles with an energy of 3keV. The magnetic field is set to 3T at the magnetic axis. We select two typical collision frequencies, ν; one is $\nu = 3.16 \times 10^3\mathrm{sec}^{-1}$, at which a 3keV electron is in the $1/\nu$ regime and the other is $\nu = 3.16 \times 10^5\mathrm{sec}^{-1}$, at which the electron is in the plateau regime. Figure 1 shows the normalized mono-energetic transport coefficients, $D^*(= D/D_p)$, in the $1/\nu$ and the plateau regimes. The transport coefficients are normalized by the plateau value of the equivalent circular tokamak, $D_p = (\pi/16)(v^3/\iota R\omega_c^2)$, where v, R, ι and ω_c are the electron velocity, the major radius, the rotational transform, and the cyclotron frequency, respectively.

We can see a strong reduction of the diffusion coefficient by shifting the magnetic axis inwards from $R_{ax} = 3.75$m and an optimum point is found around $R_{ax} = 3.53$m in the $1/\nu$ regime in Fig. 1 (top). Interestingly, the radial dependence of the optimum axis position is weak and the optimum positions are at $R_{ax} = 3.53$m in the $r/a = 0.5$ and 0.75 cases, and at $R_{ax} = 3.54$m in the $r/a = 0.25$ case. Thus, although a bit arbitrary, we shall define the $R_{ax} = 3.53$m configuration as the neoclassical-transport-optimized configuration of the LHD.

The shift of the magnetic axis alters the magnetic field configuration in flux coordinates. Figure 2 shows the Fourier spectrum of the magnetic field as a function of the normalized plasma radius (left) and the variation of the magnetic field strength along a magnetic field line (right). Three typical cases are plotted with different magnetic axis position; $R_{ax} = 3.75$m (top) , 3.6m (middle), 3.53m (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 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 component $B_{1,10}$, which is a side band term of $B_{2,10}$. The variation of the magnetic field strength shows modulations with long and short periods due to the two dominant components. This is the typical behavior of the magnetic field variation in a heliotron device.

Shifting the magnetic axis inwards to R_{ax} = 3.6m, 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 behavior of the magnetic field variation changes and the minima of the helical ripples have nearly the same B value. This indicates that the $R_{ax} = 3.6$m configuration conforms to a "σ-optimized" field[12], where the neoclassical transport is significantly improved relative to a standard heliotron configuration. As a result, the neoclassical transport coefficient of the $R_{ax} = 3.6$m case is about ten times lower than that of the $R_{ax} = 3.75$m case (Fig. 1).

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 variation of the magnetic field shows that the minima of the helical ripples are no longer constant and that the ripple becomes very small on the outside of the device. A similar behaviour of the magnetic field variation is also seen in optimized helias configurations, in which an important role of the toroidal mirror term has been discussed[13]. 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 plateau regime (bottom of Fig. 1) the diffusion coefficient decreases monotonically by shifting the magnetic axis inwards. This is due to the reduction of $B_{1,0}$, and also the coupling of the toroidal and helical contributions by $B_{1,10}$[10]. A similar coupling of the toroidal and helical contributions in the plateau regime is also found in helias configuration[14].

Figure 3 shows the mono-energetic transport coefficients at half of the plasma radius as a function of the normalized collision frequency, $\nu^*(=\nu R/v_t)$ in the three configurations; $R_{ax}=3.53$m, 3.6m, and 3.75m. We can see a strong reduction of the transport coefficient in both the $1/\nu$ and plateau regimes as the magnetic axis is shifted inwards. In the $R_{ax}=3.53$m configuration the neoclassical transport in the $1/\nu$ regime is about 30 times lower than that of the $R_{ax}=3.75$m configuration. This illustrates that neoclassical transport can be improved drastically by a strong inward shift of the magnetic axis in the LHD.

In order to compare the neoclassical transport level with that of other devices, the effective helical ripple for $1/\nu$ transport, ε_{eff}, is evaluated by the relation between the transport coefficients and collision frequency in the $1/\nu$ regime. Figure 4 shows the radial profile of ε_{eff} in the $R_{ax}=3.53$m configuration evaluated by DCOM, DKES[15][16] and a recently developed analytic formula by C.D. Beidler, et. al[17]. All three results show a very small value of ε_{eff} with the values obtained less than 1% up to $r/a=0.5$ and less than 2 % up to $r/a=0.8$. Beyond $r/a=0.8$, ε_{eff} increases rapidly up to 5 %. This result indicates that the neoclassical transport properties of the $R_{ax}=3.53$m configuration are comparable with those of "advanced stellarators". Additionally the rapid increase of ε_{eff} at the plasma edge would be advantageous for density control in a reactor, which has been identified as a potential problem for certain helias-type reactors[18].

In this study, vacuum fields have been chosen to illustrate the fundamental properties of a strongly inward-shifted configuration. The Shafranov shift at finite plasma pressure leads to a deterioration in the confinement but can be partially compensated by additional vertical field. Such studies will be carried out in the future.

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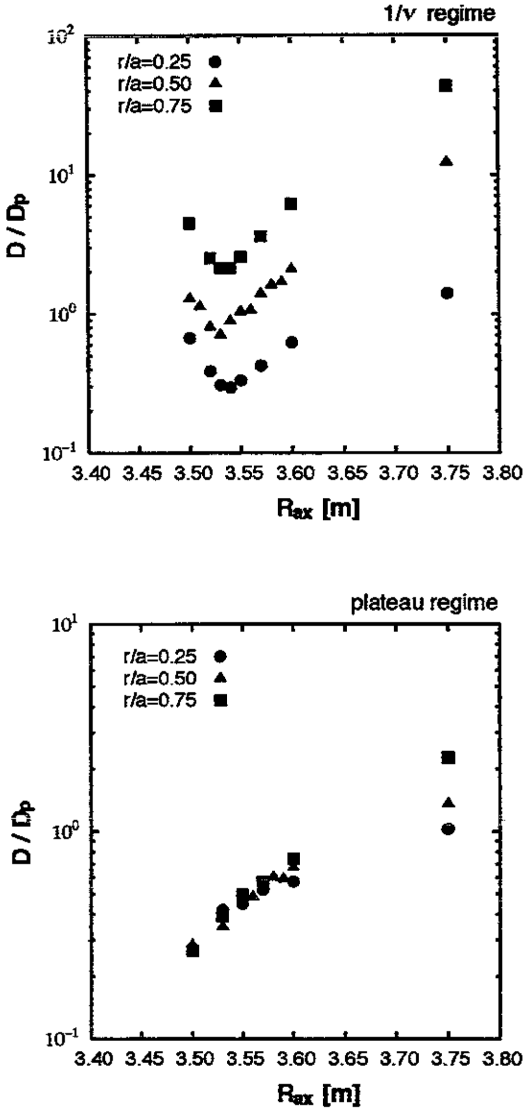

Fig. 1: Plots of the normalized neoclassical transport coefficients evaluated by DCOM as a function of the magnetic axis position for $\nu=3.16\mathrm{x}10^{3}$Hz in the $1/\nu$ regime (top) and for $\nu=3.16\mathrm{x}10^{5}$Hz in the plateau regime (bottom).

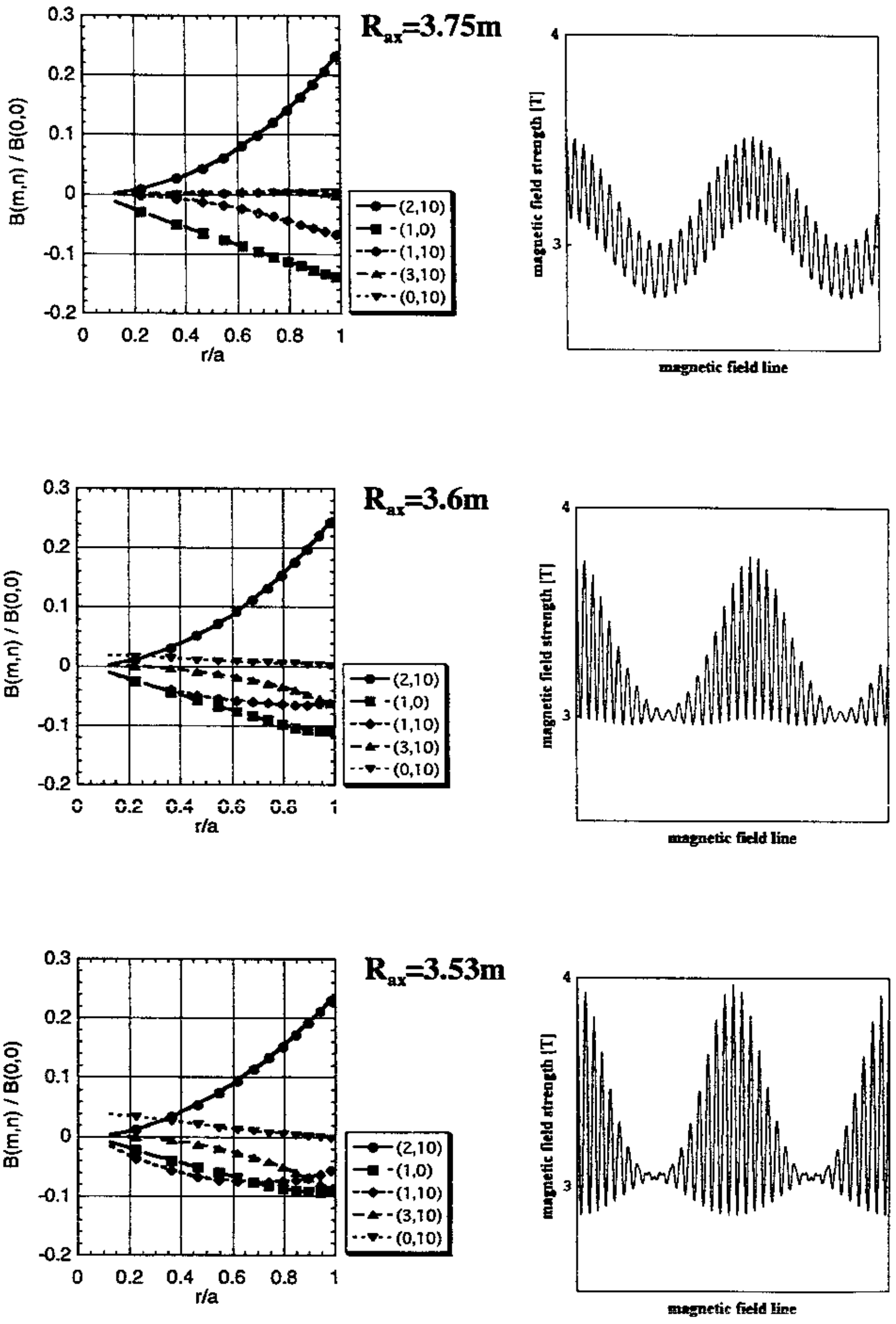

Fig. 2: Radial profiles of the Fourier spectrum of the magnetic field as a function of the normalized plasma radius (left) and the variation of magnetic field strength along the magnetic field line (right) in three typical configurations; R$_{ax}$=3.75m (top), 3.6m (middle), and 3.53m (bottom).

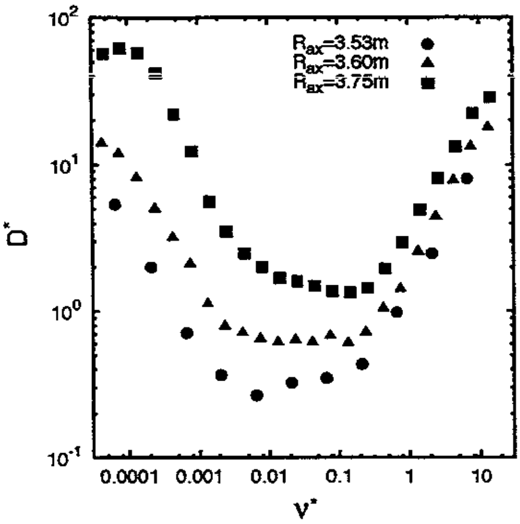

Fig. 3: Plots of the mono-energetic neoclassical transport coefficients at a half of the plasma radius as a function of the normalized collision frequency in the three typical configurations; R_{ax}=3.75m, 3.6m, and 3.53m.

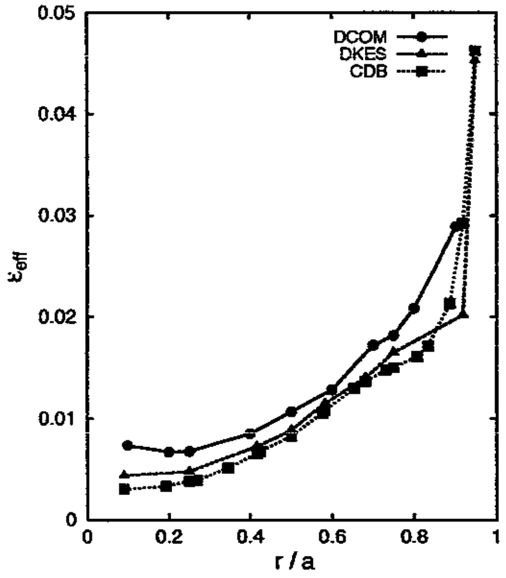

Fig. 4: Radial profiles of the effective helical ripple in the R_{ax}=3.53m configuration evaluated by DCOM, DKES and an analytic formula.

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