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Physics Studies on Helical Confinement Configurations with ℓ=2 Continuous Coil Systems

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ABSTRACT

The physics studies have been carried out to optimize ℓ=2 heliotron/torsatron configurations having continuous coil system for the Large Helical Device (LHD), focusing on beta-orbit-divertor compatibility requirement, neoclassical & anomalous transports, bootstrap & Ohkawa currents, and divertor layer analysis.

The optimal m number is found $\sim$ 10 for the LHD system based on three physics criteria: MHD stability ($\beta \gtrsim 5\%$), particle orbit confinement (loss-cone-free radius $r_L \gtrsim \frac{1}{3}a_p$ (plasma minor radius)) and clean divertor layer (divertor-wall clearance $\Delta_{dw} \gtrsim$ 3cm). The pitch parameter of helical coil γ_c is determined mainly from the beta-divertor condition. For the detailed prediction of LHD plasma parameters, 2.5-dimensional equilibrium-transport simulations including empirical or drift wave turbulence models are carried out, which reveal that the global confinement time is sensitive to the edge electron anomalous transport although ripple loss through the ion channel is dominant in the plasma core. When ripple-transport-optimized configurations are adopted, the bootstrap current is increased; however, the Ohkawa current may be utilized cancel this current. The divertor layer study clarifies peculiar magnetic properties of thin curved divertor layers and suggests the effectiveness of helical divertors.

From these physics considerations within the related engineering constraints, a final standard LHD configuration (m=10, γ_c=1.25, α^*=0.1, where m, γ_c and α^* are toroidal mode, pitch and pitch modulation parameters of the helical coil, respectively) is determined.

KEYWORDS: large helical device, physics design optimization, MHD beta limit, particle loss, neoclassical transport, anomalous transport, drift wave turbulence, bootstrap current, Ohkawa current, helical divertor

1. INTRODUCTION

Helical systems have distinct advantages in performing steady-state operations without plasma current disruptions. To demonstrate these advantages using built-in helical divertor configuration, the Large Helical Device (major radius R ~4m, magnetic field B ~4T, plasma minor radius $a_p \sim 0.6$m) [1] is started to be built. The ℓ=2 continuous coil system is adopted for LHD because of its clean divertor configuration and enough experimental database. Related to this Project, physics studies extended from the previous work [2] have been carried out to optimize heliotron/torsatron configurations within the engineering constraints [3,4] with respect to physics requirements such as high beta achievement ($\beta \gtrsim 5\%$), good high-energy-particle confinement (loss-cone-free radius $r_L \gtrsim \frac{1}{3}a_p$ for 70% ICRF heating efficiency), enough divertor-wall clearance ($\Delta_{dw} \gtrsim 3$cm) , and optimization of transport properties.

2. MHD BETA AND PARTICLE ORBIT CONFINEMENT

The low m (toroidal period number) system has good MHD properties, but the particle orbit confinement is a concern. This orbit problem is significantly mitigated by the inward shift of the plasma column. Extensive studies on high beta stability in LHD have been done using H-APOLLO and H-ERATO codes [2], and orbit confinement conditions for high heating efficiency have been analyzed by using parallel adiabatic invariants [5]. The beta-divertor condition mentioned in section 1 dictates the m-number below ~10 for medium γ_c configuration ($\gamma_c \equiv \frac{m a_c}{\ell R} \sim 1.2 - 1.3$, a_c is minor radius of helical coil), as shown in Fig.1(a). Higher γ_c configuration ($\gamma_c \gtrsim 1.3$) is not appropriate with respect to the divertor-wall clearance for 4m/4T LHD designs. Figure 1(b) shows beta-orbit conditions in terms of m-number and inward shift percentage of the plasma axis ($\delta_{ax} \equiv \frac{\Delta_{ax}}{R}$), which suggests that a configuration with m=10 (γ_c =1.20) and slight inward shift ($\delta_{ax} = -3\%$) is optimum.

In LHD a slight positive pitch modulation of helical windings ($\alpha^* = 0.1$, $\theta \equiv \frac{m}{\ell}\phi + \alpha^*$ sin $(\frac{m}{\ell})\phi$) is found to improve the physics and engineering compatibility. The positive pitch modulation leads to more improvement in orbit confinement for large inward shift ($\delta_{ax} \lesssim -3\%$) than the negative pitch modulation.

The detailed engineering design makes high coil current density available (up to 53.3A/mm^{-2} at R=4.0 m and B=4.0 T) , which permits the higher γ_c configuration (up to 1.25) and gives rise to the higher beta achievement without deterioration of the orbit confinement compared with the $\gamma_c = 1.20$ configuration.

3. NEOCLASSICAL AND ANOMALOUS TRANSPORTS

For the analysis of the LHD transport, two and half dimensional equilibrium-transport simulations (combination of 3D-equilibrium VMEC [6] and 1D-transport HTRANS codes) with NBI deposition and its slowing-down calculations have been done which take into account several anomalous transports as well as neoclassical transport. A neoclassical ripple transport model adopted here includes radial electric field and multi-helicity effects of magnetic configurations, and its validity is checked by the DKES code [7]. As for anomalous transports, modifying the global LHD scaling [8], we adopted (1) an empirical semi-local transport coefficient with an improvement factor f_{imp},

$$\chi_{emp}(r) = 1.47 f_{imp}^{-1} P^{0.58} B^{-0.84} R^{-0.75} n(r)^{-0.69}$$

or (2) a drift wave turbulence (DWT) model [9] added with helical ripple contribution (ϵ_h: helical ripple) on the collisionless and dissipative trapped electron modes (CTE and DTE):

$$\chi_{hte}(r) = \frac{5}{2} \min\left(\sqrt{\epsilon_h}\frac{\omega_{*e}}{k_\perp^2}, \sqrt{\epsilon_h}\frac{\omega_{*e}}{k_\perp^2}\frac{\omega_{*e}}{(\nu_{ei}/\epsilon_h)}\right).$$

These models do not contradict with CHS experimental data of Ref. [10] as shown in FIG.2.

Typical simulation results of 20 MW NBI-heated LHD plasmas are shown in FIG.3 for (a) empirical scaling with $f_{imp} = 1.0$ and (b) electrostatic DWT model. Neglecting anomalous particle inward flows, flat or hollow density profiles are obtained as seen in the existing experiments. The empirical electron thermal conductivity is larger than the neoclassical values; on the other hand, the ripple contribution is not neglected for ion energy transport (FIG.3(a)). From the prediction of DWT model with neoclassical transports, the ion temperature gradient (ITG) mode due to the flat density profile is dominant in the ion transport process of the plasma core, instead of CTE, DTE, collisionless circulating electron (CCE) and collisional circulating electron (XCE) modes (FIG.3(b)). This prediction from ITG modes should be checked by the existing experiments.

Related to the effect of the magnetic configurations, a moderate positive pitch modulation of the helical coil slightly reduces the central temperature due to high ripple ion loss, but leads to a slight increase in the plasma radius and hence in the global confinement.

Moreover, the positive α^* configuration with higher effective helical ripple provides easier access to the hot ion regime with positive electric field at the low density operation.

4. BOOTSTRAP AND OHKAWA CURRENTS

Currents parallel to magnetic field lines consisting of the bootstrap current, Ohkawa current, and Spitzer current in LHD are analyzed in the banana regime using the flux-friction relation. The bootstrap current depends strongly on the magnetic geometry because of the strong dependence of the radial diffusion on the magnetic field structure. Vertical elongation of the toroidally averaged magnetic surface, outward shift of the magnetic axis, and positive pitch modulation of the helical coils make the bootstrap current small. Especially, vertical elongation is effective [11,12]. However, its dependence on the geometry is opposite to that of the particle orbit confinement. In the optimal configuration discussed in section 2, the bootstrap current amounts to 150-300 kA depending on the density profile. The neoclassical conductivity and the ratio of the net Ohkawa current to the fast ion current have the same expressions as ones in a tokamak case because the source term is insensitive to the detailed magnetic field structure. Influences of the magnetic field structure appear through the fraction of trapped particles. The Ohkawa current is obtained using the electron drift kinetic equation [13] as well as moment approach, which suggests that an ion rotation does not contribute to the Ohkawa current. A unidirectional parallel injection of hydrogen atoms with 10 MW and 120 kV generates a current of roughly 100 kA. One method to reduce the total plasma current is to balance the bootstrap current by the Ohkawa current, if needed.

5. HELICAL DIVERTOR STUDY

The helical divertor is a key ingredient of the LHD device. Like good tokamak divertor, the LHD configuration has a good capability of recycling control and high edge shear, two possible key conditions for achieving good H-mode. The major difference between the helical and tokamak divertors is the magnetic configuration.

The LHD configuration can be divided into four regions: 1) the stochastic region just outside the last closed surface, which is due to overlapping of the natural islands with toroidal mode number of 10, 2) the divertor thin curved layers, as shown in FIG.4, which is caused by the existence of high “local” magnetic shear at the periphery on the large major radius side of the torus and the radial movement of the “X-point” [14], 3) the inter-thin curved layer region, in which field lines directly connect two different points on the divertor plates within several helical pitches, and 4) the divertor channel with very short filed line length ($\sim \pi \ell R/m$) beyond the “X-point”.

The heat flux from the core plasma region first passes through the stochastic region and flows along the divertor thin curved layers with connection length of $\gtrsim 3 \times 2\pi R$. Then it flows into the divertor channel (region 4) and reach the divertor plates. The most important design requirement for the divertor is that these thin curved layers do not touch the first wall, which is satisfied in the present LHD design.

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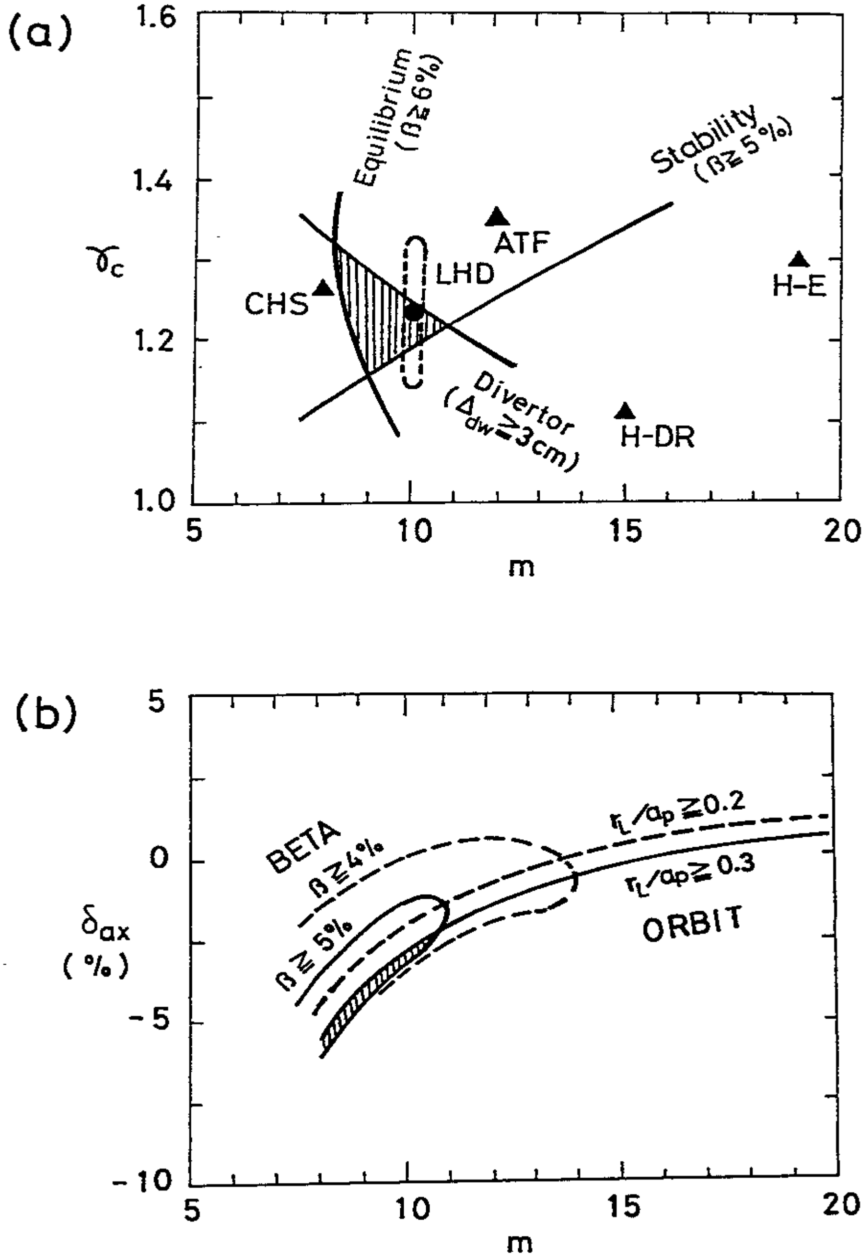

FIG.1 Schematic m-γ_c and m-Δ_{ax} plots for LHD design optimization. Relevant physics requirements are fulfilled in the shaded area.

(a) Beta and divertor constraints.

The divertor condition is shown for 4m/4T machine with coil current density of 53.3A/mm^2. Other helical devices are plotted in the same figure. In LHD the helical pitch parameter γ_c is adjustable by the multi layer operation of the helical coils.

(b) Beta and loss-cone-free conditions.

Appropriate coil pitch parameter γ_c is chosen for each m number ($\gamma_c = 1.15, 1.20, 1.23, 1.25$ and 1.30 for $m = 8, 10, 12, 14$ and 19, respectively).

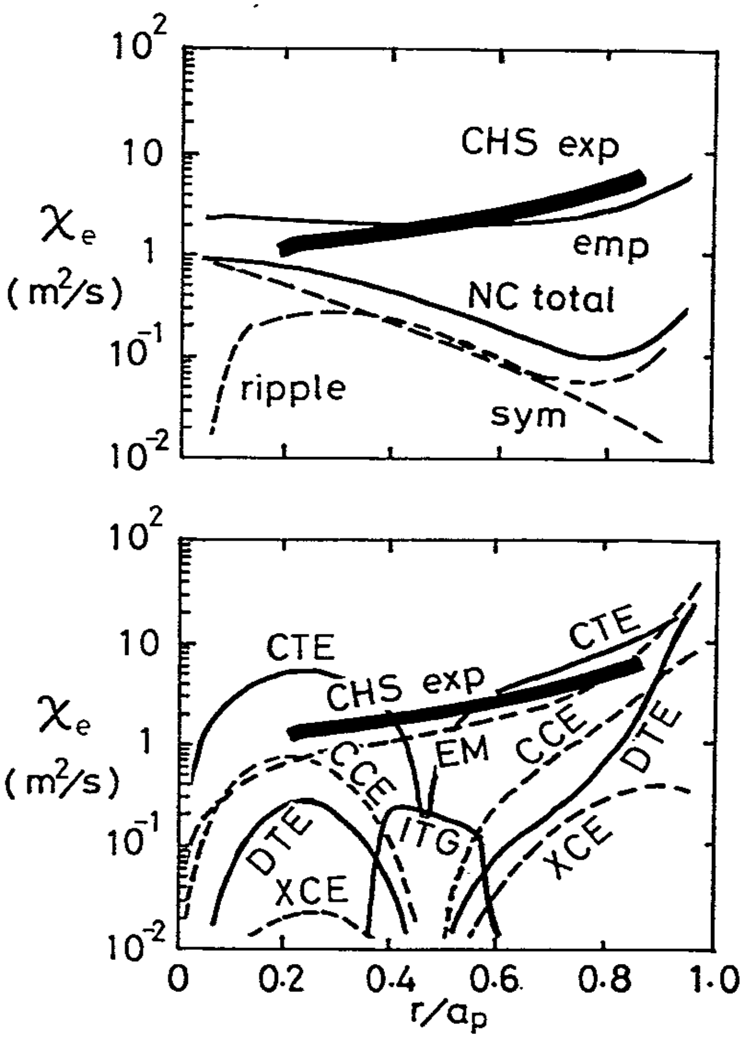

FIG.2 Comparisons of adopted thermal conductivities with CHS experimental data[10].

Neoclassical value (NC) with symmetric and ripple terms and empirical anomalous coefficient (emp) are given in the upper figure. Drift wave turbulence models are plotted in the lower figure. In addition to several electrostatic modes, electromagnetic drift wave model (EM) is also plotted.

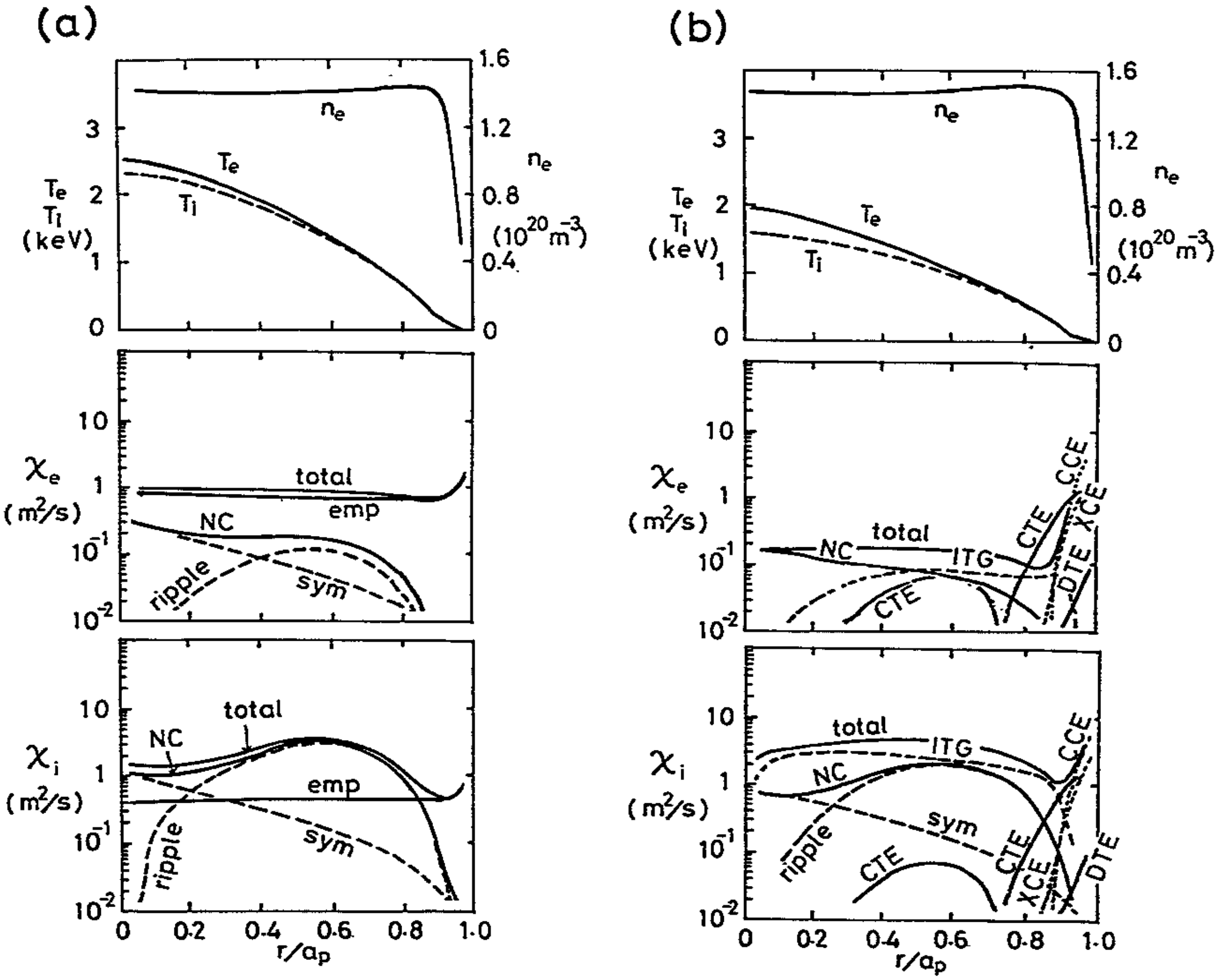

FIG.3 Transport simulations of LHD plasmas in 20 MW NBI heating case.

(a) Anomalous empirical model with neoclassical transport is used without considering confinement improvement. (average electron density: $1.25\times10^{20}m^{-3}$)

(b) Electrostatic drift wave turbulence model with neoclassical transport is adopted. (average electron density: $1.30\times10^{20}m^{-3}$)

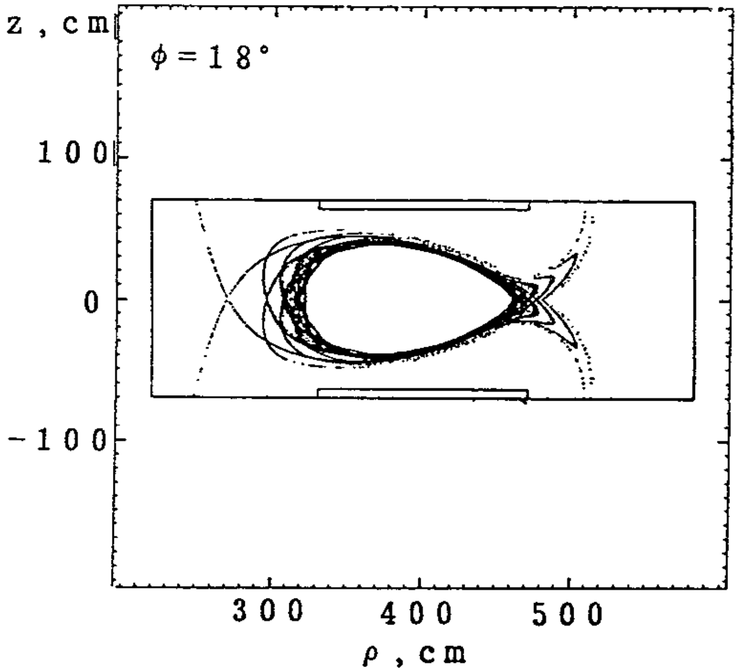

FIG.4 Puncture plots of periphery field lines for LHD divertor.

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