

Study on Energy Confinement Time and Heat Transport in Initial NBI Heated Plasmas on LHD

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1. Introduction The large helical device (LHD)¹ has extended the envelope of confinement study on currentless helical plasmas by more than one-order of magnitude in plasma size. LHD is a large superconducting heliotron with a major radius (R) of 3.8 m and a minor radius (a) of 0.6 m. The experimental data of the medium-sized helical devices ($a=0.18\sim 0.27$ m) have been accumulated in the international stellarator database, which has yielded the international stellarator scaling 95 (ISS95)². This scaling indicates that confinement in helical systems is gyro-Bohm like ($\propto \rho^{*-0.71}$). Since dependence on the normalized gyro-radius ρ^* has a great impact on extrapolation to reactor-grade plasmas, careful examination by a wide-range scan of ρ^* is prerequisite for establishment of a reliable scaling law. ρ^* is also connected to the characteristic scale length of an instability, therefore, it is attracting interest in the clarification of the physical mechanism of anomalous transport. Exploration in LHD combined with past studies in medium-sized helical devices is highlighted in this strategy. Parameter regimes studied here cover magnetic field (B) of 1.5 - 2.75 T, line averaged density (\bar{n}_e) of $1.0 - 4.9 \times 10^{19} \text{m}^{-3}$ and heating power (P_{abs}) of 0.75 - 3.2 MW. Although LHD has large flexibility in magnetic configuration, behavior only in the standard configuration which is characterized by the magnetic axis position (R_{ax}) of 3.75m and the toroidal averaged ellipticity of 1 is studied. The database in this study consists of 68 NBI-heated hydrogen discharges in quasi-steady state. All correlation between sets of the logarithm of \bar{n}_e , P_{abs} and B are less than 0.25, which indicates that independence of surveyed parameters is sufficient. Diamagnetic measurement and a variety of profile measurements, i.e., T_e profile by the YAG-thomson scattering system, T_i profile by the charge-exchange spectroscopy, n_e profile by the FIR laser interferometer, etc have been employed in this study. Absorbed power profile has been evaluated from the direct heat load measurement of port-through power and 3-D Monte-Carlo simulation³.

2. Energy Confinement Times Comparison of LHD data with available scaling laws, i.e., ISS95, the Lackner-Gottardi(L-G)⁴ scaling, the LHD scaling⁵, and the gyro-reduced Bohm (GRB) scaling⁶ indicates systematic enhancement of confinement. Enhancement factors are 1.18 ± 0.15 for ISS95, 1.15 ± 0.13 for L-G, 1.44 ± 0.16 for LHD, and 1.40 ± 0.18 for GRB. To exclude magnetic configuration effect, the database of LHD has been combined with the data from Heliotron-E, ATF and CHS since they have a common physical concept. The regression analysis of the past heliotrons has given the scaling;

$$\tau_E^{sc1} = 0.04 a^{2.06} R^{0.74} B^{0.83} P_{abs}^{-0.63} \bar{n}_e^{-0.53} t_{2/3}^{0.39}$$

where the units of τ_E in s, P_{abs} in MW and \bar{n}_e in 10^{19}m^{-3} are used and $t_{2/3}$ is the rotational transform at the two thirds radius (0.58 in LHD). The present data of LHD lies well above this scaling (see Fig.1(a), the fitting quality of R^2 is 0.926 for the medium devices). A simple statistical analysis of the combined database including LHD data has given an unusual expression which does not satisfy the dimensional constraints^{7,8};

$$\tau_E = 0.37a^{3.22}R^{0.20}B^{0.86}P_{abs}^{-0.61}\bar{n}_e^{-0.52}t_{2/3}^{0.93}.$$

This cannot be judged to be valid in extrapolation. Regression analysis of LHD data alone gives $\tau_E = 0.05B^{0.71}P_{abs}^{-0.61}\bar{n}_e^{-0.57}$

which is rewritten into $\tau_E = \tau_E^B \rho^{*-0.83} \nu^{*0.01} \beta^{0.08} q^{-0.01} L^{2.82}$, where L with the dimension of length is selected to have correct dimensions. Although the unified size scaling is not easily resolved, the dependence on density, magnetic field and absorbed power is robust and suggests gyro-Bohm type characteristics in LHD as well.

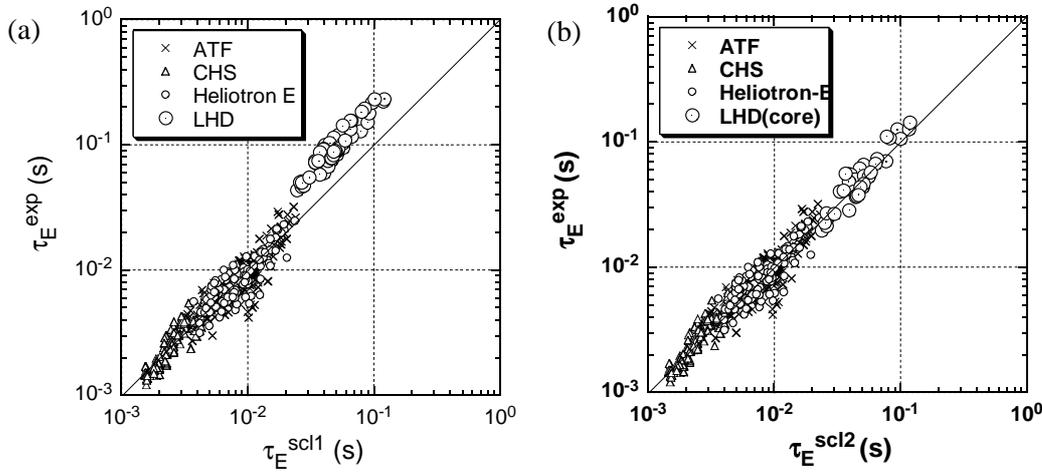


Fig.1 Comparisons of energy confinement times with the scalings. (a) Scaling derived from Heliotron E, ATF and CHS. (b) Scaling derived from combined database of three medium device and core part of LHD.

The major characteristic of LHD plasmas which is different from the past medium heliotrons is the formation of an edge pedestal. The ratio of the temperature at the pedestal to the average temperature reaches as high as 0.8. This is contrast to the fact that the plasma pressure in medium-sized heliotrons decreases asymptotically to zero towards the last closed flux surface, which leads to the hypothesis that the confinement region can be divided into the core and the pedestal. In medium heliotrons, the part of pedestal is negligible. The core region, here, is defined by a subtraction of the pedestal at $\rho = 0.9$, where ρ is the normalized minor radius, from the whole for simplicity. A statistical analysis of data from the combination of the core confinement in LHD and the whole confinement of the medium heliotrons gives the best fitting ($R^2 = 0.949$) expression of

$$\tau_E^{scl2} = 0.04a^{2.09}R^{0.74}B^{0.80}P_{abs}^{-0.63}\bar{n}_e^{-0.54}t_{2/3}^{0.39}.$$

Figure 1(b) illustrates the comparison of experimental data of this scaling. This expression is essentially the same as that derived from the medium devices only and rewritten into the following nearly dimensionally correct equation;

$$\tau_E \propto \tau_E^B \rho^{*-0.51} \nu^{*0.07} \beta^{-0.34} q^{-1.15} A_p^{0.3} a^{-0.05}. \quad (1)$$

Confinement in the core region of LHD is weakly gyro-Bohm like, which is consistent with the precedent understanding. A systematic enhancement of confinement is attributed

to the contribution from the pedestal.

All scalings for helical systems indicate a positive density dependence unlike tokamak L-mode. A linear dependence on density is observed ohmically heated plasmas, which is lost in the high density regime. Power deposition density is correlated with this saturation⁹. Figure 2 shows the density scan with the same heating power (1.4 – 1.5 MW). In the presently available range of density, confinement time can be scaled by $\bar{n}_e^{0.5-0.6}$. From the tokamak experience, saturation should occur at $\bar{n}_e = 2 \times 10^{19} \text{m}^{-3}$.

3. One-Dimensional Heat Transport

A 1-D local heat transport analysis also has been progressing to clarify confinement characteristics complementing global confinement analysis. The dimensionless parameters ρ^* , β , v^* are attracting interest as key parameters in determining the transport process. In particular, ρ^* is most important in both physics and engineering design. In contrast to ρ^* , it seems that β and v^* are less important because they do not significantly effect confinement and reactor grade values already have been achieved. Here it should be noted that v^* can be important through neoclassical transport in the collisionless regime in helical plasmas when anomalous transport is suppressed sufficiently. Since ρ^* cannot be scanned over a wide range in a single device, comparison of experiments in two devices with different sizes is effective. Figure 3 shows the radial profiles of v^* , ρ^* and β in CHS ($a \sim 0.20\text{m}$) hot-ion mode discharge¹⁰ and LHD ($a \sim 0.58\text{m}$). Here two discharges with similar v^* are chosen. Collisionality is almost the same up to $\rho = 0.8$. A normalized gyro-radius of CHS is larger than that of LHD by a factor of 2 in $\rho < 0.7$. Since the high edge temperature distinguishes LHD from CHS, their collisionality and normalized gyro-radius show different trends in the peripheral region. Since the temperature drops towards zero in CHS, the collisionality increases rapidly and the gyro-radius decreases. In LHD both change much more gradually. The physical picture of gyro-Bohm type transport predicts that heat transport is improved in LHD due to smaller ρ^* and that this trend is reversed in the edge. Since the Bohm factor ($D_B \propto T/B$) of LHD is twice as large as that of CHS, heat conduction should be the same in the core region.

Figure 4(a) shows the electron heat conduction coefficients of CHS and LHD. In the core region, LHD is better than CHS by a factor of 2 – 3. The heat conduction in CHS is much enhanced in the edge region while LHD has an almost flat profile. With regard to comparison with neoclassical theory, a deterioration factor is suppressed up to around 3 in LHD although it has the order of 10 – 10² in CHS. However, anomalous transport is still dominant in electron heat transport in LHD although collisionality enters the collisionless regime where helical ripple transport plays an essential role. Differences

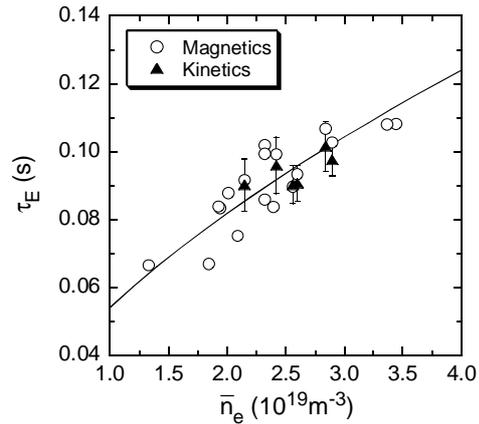


Fig.2 Density dependence of energy confinement. A solid line is $\bar{n}_e^{0.6}$ as a reference.

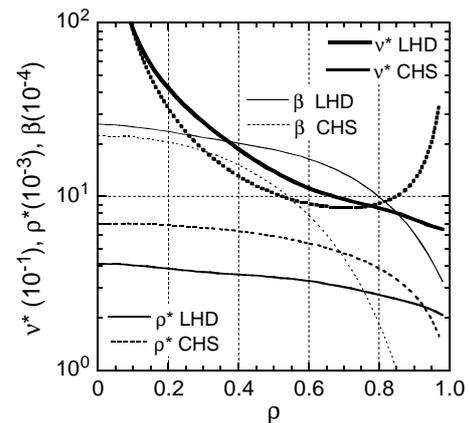


Fig.3 Dimensionally similar discharges in CHS and LHD.

in the ion transport of CHS and LHD is smaller than in electrons except for the edge region (see Fig.4(b)) and deterioration in the edge region is observed in CHS as in the electron transport. In contrast to electrons, ion transport is close to neoclassical in both CHS and LHD although it should be noted that more precise argument awaits information of radial electric field which has significant effect on ion transport. The difference in heat transport coefficients between CHS and LHD does not contradict the physical picture of gyro-Bohm in the core region. If ρ^* dependence does not exist, the transport in LHD should be worse by a factor of 2 than in CHS. In the edge region, however, experimental observation is clearly inconsistent with gyro-Bohm type transport. The values of both heat conduction coefficients for ions and electrons are close to each other in LHD. This fact also suggests that the predominant instability is electrostatic, which is consistent with gyro-Bohm type transport.

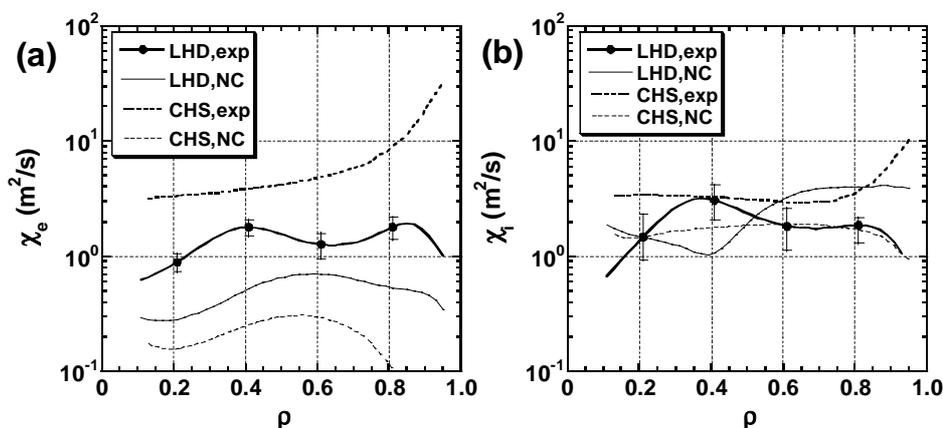


Fig.4 Heat conduction coefficients. (a) electrons. (b) ions. NC denotes neoclassical prediction with no electric field.

4. Discussions and Conclusions Global energy confinement studies indicate the core confinement is weakly gyro-Bohm like and confinement enhancement is attributed to formation of an edge pedestal. This is also phenomenologically consistent with the experimental observation that confinement deteriorates when the edge pedestal is lost due to strong gas puff or strong magnetic perturbation by local island divertor coils. Although the ρ^* dependence of LHD plasmas ($\rho^{*-0.83}$) is stronger than Eq.(1) ($\rho^{*-0.51}$), it is weakened when only the core part is considered. Local transport analysis indicates that core confinement does not contradict gyro-Bohm although the edge behavior is clearly inconsistent with it. This observation agrees quite well with the understanding of energy confinement characteristics and with the plasma profiles.

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