Effect of Ellipticity on Thermal Transport in ECH Plasmas on LHD

H.Yamada, M.Yokoyama, S.Murakami[a], K.Y.Watanabe, H.Funaba,
Y.Narushima, S.Sakakibara, T.Morisaki, Y.Nagayama,
S.Kubo, T.Shimozuma, K.Tanaka, T.Tokuzawa, I.Yamada and LHD Experimental Group

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

a Dept. of Nucl. Engr., Kyoto Univ., Yoshida-honmachi, Sakyo, Kyoto 606-8501, Japan

Effect of ellipticity on thermal transport has been investigated for ECH plasmas in LHD. Ellipticity κ is scanned from 0.8 to 1.4 by controlling quadrupole magnetic field. Experimental data of energy confinement time align with the scaling for all configurations, however, there exist systematic offsets. Performance $\tau_E^{exp}/\tau_E^{ISS04}$ is summarized as 0.94±0.02 for κ=0.8, 1.41±0.07 for κ=1.0, and 0.91±0.03 for κ=1.4. Local transport analysis based on power balance indicates that plasma transport is predominated by anomalous transport. However, the observed anomaly shows correlation with the change of an effective helical ripple ε_{eff}. Physical background of this correlation, the dependence on the poloidal viscous damping rate C_p is discussed. The present experimental comparison suggests a negative evidence for relevance of C_p.

Keywords: Thermal transport, Configuration effect, Neoclassical transport, Anomalous transport, Net-current free plasmas, Ellipticity

1. Inroduction

Exploration of the effect of magnetic configuration on confinement is prerequisite for optimization of a helical system. Extensive efforts in experiments as well as theories have been done. Geometrical optimization for the neoclassical transport has been demonstrated in NBI plasmas on LHD and the anomalous transport has been suppressed as well in the neoclassical optimized configuration [1]. In these configuration studies, the position of the magnetic axis is the key control parameter [2].

International collaboration for the stellarator/heliotron confinement database has progressed [3-6] and a comprehensive comparative study has suggested that net-current free plasmas have robust and similar dependence on magnetic field, density and heating power [3-5]. Gyro-Bohm nature explains experimental trend in a variety of devices quite well, like in the ISS04 scaling [5];

$$\tau_E^{ISS04} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \bar{n}_e^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$
$$\propto \tau_{Bohm} \rho^{*-0.79} \beta^{-0.19} \nu_b^{*0.00} \iota_{2/3}^{1.06} \varepsilon^{-0.07}$$

Together with confirmation of this commonality, existence of systematic offsets between different configurations/devices has been pointed out. These device/configuration dependent offsets have been quantified by comparisons of subsets which reflect characteristic configurations, however, physical background of this quantity has not been clarified yet. The measure of the offsets correlates with the effective helical ripple ε_{eff} which is characterized by the neoclassical helical ripple transport in the collisionless 1/ν regime [5]. It should be noted that the transport in experiments itself is significantly larger than the neoclassical transport. Since the anomalous transport is predominate, a physical picture of neoclassical transport is not directly applicable to explain experimental observation. Therefore these observations postulates a working hypothesis that neoclassical optimization can suppress anomalous transport.

Large flexibility of the coil system of LHD enables us configuration scan other than the position of the magnetic axis, i.e., plasma elongation. Although the plasma elongation scan for NBI heated plasmas have been already reported [1], ECH plasmas which are located in the collisionless regime have not been studied yet.

2. Experimental Set-up

Plasma elongation has been controlled by the quadrupole field and scanned in the range between κ=0.8 and 1.4 (see Fig.1). Here elongation is defined by the toroidal averaged value since the elliptic surface rotates along the toroidal angle. The position of the magnetic axis R_{ax} is fixed at 3.6m. The magnetic field is fixed at 1.5 T, which provides centrally well focused deposition of ECH with 84GHz. The plasma volume, in other words, the plasma minor radius is kept the same by the control of the effective aspect ratio of helical coil. A helical coil consists of 3 blocks with independent power supplies, which can change the effective current center of the helical coil. Although the Shafranov shift and resultant change in rotational transport is sensitive to ellipticity [7], finite-β effect is not significant in the present study since the β is

author's e-mail: hyamada@LHD.nifs.ac.jp

limited to 0.3% in ECH plasmas.

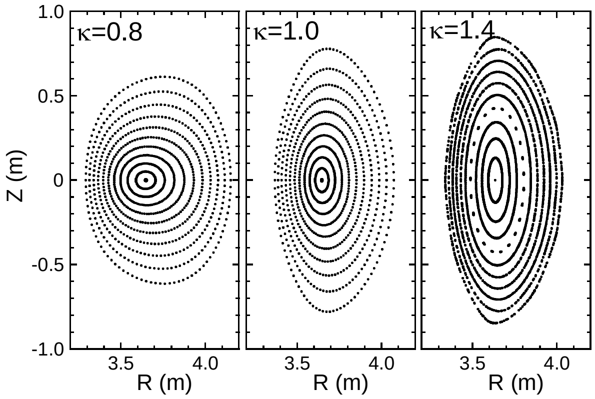

Fig.1 Magnetic flux surfaces for elongation scan. Cross-section at vertical elongated position where the helical coils are located on the equatorial plane.

In this study, the poloidal viscous damping rate is explored as a potential key parameter to bridge the neoclassical optimization and suppression of anomalous transport. Generally speaking, zonal flows are generated efficiently in the configuration with low poloidal viscosity and then suppression of anomalous transport is anticipated in such a configuration. The poloidal viscous damping rate C_p [8] is plotted with ε_{eff} for R_{ax} in Fig.2. Since C_p is affected by a toroidal curvature as ε_{eff}, C_p and ε_{eff} has a clear correlation. Indeed, in the standard ellipticity κ=1.0, both quantities have the same trend for R_{ax} and become the minimum in the vicinity of R_{ax}~3.6m where high performance can be obtained in the experiment.

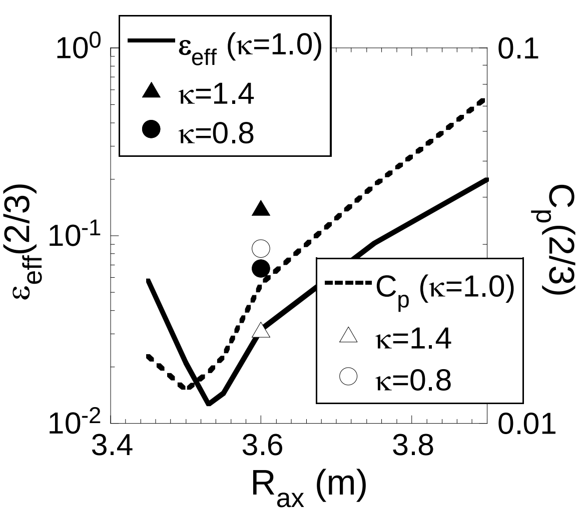

Fig.2 Dependence of effective helical ripple ε_{eff} and poloidal viscous damping rate C_p on the position of the magnetic axis. Elongation scans are plotted by triangles and circles at R_{ax}=3.6m.

Therefore which parameter; ε_{eff} or C_p is more essential in transport cannot be distinguished. However, plasma elongation can separate these two effects. As seen in Fig.2, a vertically elongated configuration (κ=1.4) has larger ε_{eff} than the standard configuration (κ=1.0) while it has smaller C_p.

3. Experimental Results

Two dimensionally similar discharges with different elongation have been compared to clarify the elongation effect on heat transport. The line averaged density is controlled at $1\times10^{19}\text{m}^{-3}$ and electron temperature is also controlled to be the same in two case with κ=0.8 and 1.0 (see Fig.3). Heating power is also controlled to realize the same electron temperature (see Fig.4)

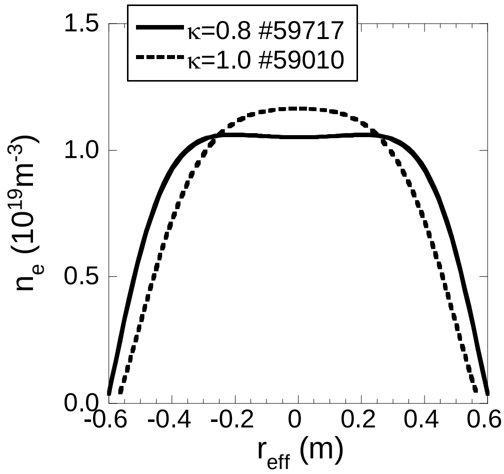

Fig.3 Electron density profiles in discharges with different elongation.

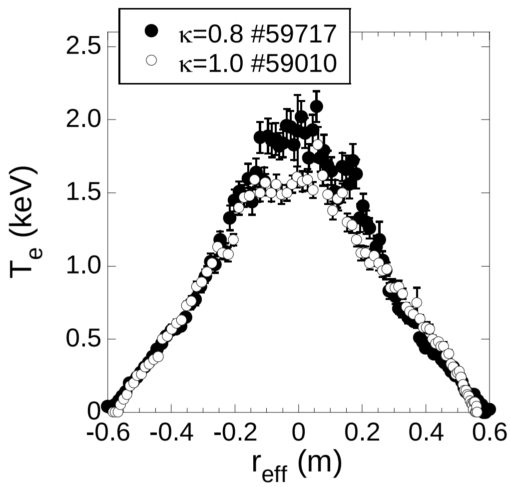

Fig.4 Electron temperature profiles in discharges with different elongation.

Here it should be noted that the investigated plasmas lie in 1/ν regime and that they do not enter so deeply in collisionless regime that electric field effect on neoclassical transport is not significant. Since the case with κ=1 shows the better confinement, the heating power is 0.93 MW for κ=0.8 and 0.35 MW for κ=1. The plasma parameters except for the elongation are similar to each other, therefore, representative non dimensional physical parameters such as normalized gyro-radius ρ*, collisionality ν*, and beta are also similar to each other.

Figure 5 shows the ratio of the electron heat diffusivity of these two cases. Since the plasma parameters of these two cases are the same, the deviation of this ratio from 1 can be attributed to the remained difference, i.e., elongation. Corresponding to the global confinement nature, local heat diffusivity in the experiment shown in a solid curve indicates enhancement of heat transport in the case with κ=0.8 by a factor of 2 to 3. A dotted line is the prediction from neoclassical theory. These two curves are close to each other, which suggest the neoclassical transport may make the difference in heat transport. However, this is not the case. Figure 6 shows the heat diffusivity profile. The fat solid curve is the experimental value in the case with κ=0.8 and the dotted fat curve is the corresponding neoclassical prediction. The experimental value is significantly larger than the neoclassical value, which indicates heat transport is anomalous even for the case with κ=0.8. Therefore, this is another example that configuration effect on anomalous transport is correlated or accidentally happens to coincide with nature of neoclassical transport [5].

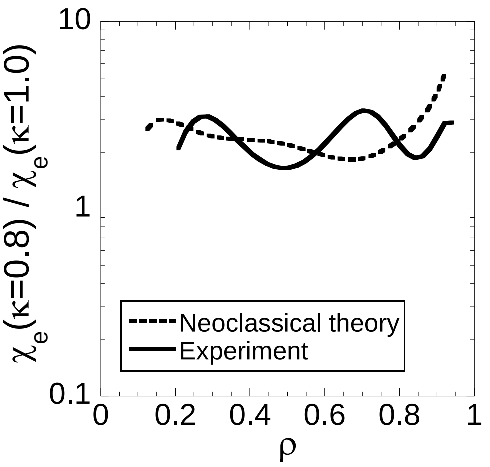

Fig.5 Ratio of heat diffusivity of two discharges with different elongation

Figure 7 shows the comparison of experimental energy confinement time with the prediction from the ISS04 scaling for plasmas with different ellipticity as shown in Fig.1. Energy confinement times have the maximum performance at κ=1 and degrades in both prolate (κ>1) and oblate (κ<1) directions. These trends agree with the observation in NBI heated plasmas [2].

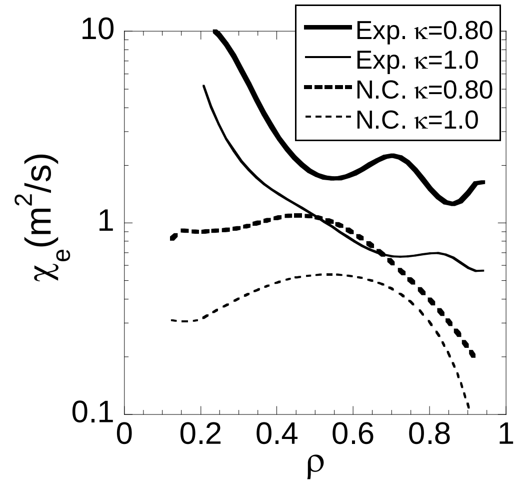

Fig.6 Experimental and neoclassical heat diffusivity.

Experimental data align with the scaling for all configurations. Each performance $\tau_E^{exp}/\tau_E^{ISS04}$ is summarized as 0.94±0.02 for κ=0.8, 1.41±0.07 for κ=1.0, and 0.91±0.03 for κ=1.4. If the C_p is more relevant parameter, the confinement should become the maximum at κ=1.4. However, the experiments indicate that the confinement is the best at κ=1.0 and declined by the both prolate (κ=1.4) and oblate (κ=0.8) modifications. The present experimental comparison suggests a negative evidence for relevance of Cp.

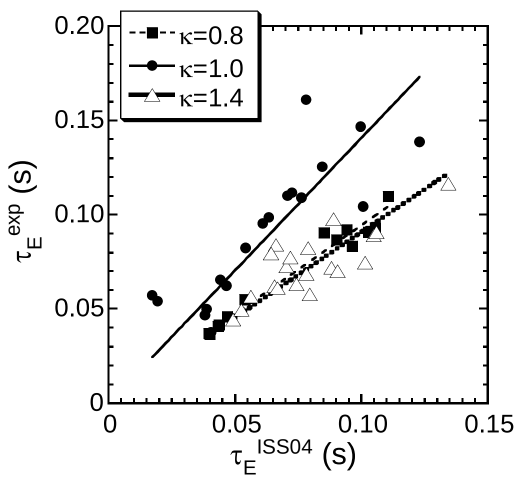

Fig.7 Comparison of experimental energy confinement time with prediction from the ISS04 scaling

4. Conclusions

Effect of ellipticity on thermal transport has been investigated for ECH plasmas in LHD. Ellipticity κ is scanned from 0.8 to 1.4 by controlling quadrupole magnetic field. Experimental data of energy confinement time align with the scaling for all configurations, however, there exist systematic offsets. Performance $\tau_E^{exp}/\tau_E^{ISS04}$ is summarized as 0.94±0.02 for κ=0.8, 1.41±0.07 for κ=1.0, and 0.91±0.03 for κ=1.4. Local transport analysis based on power balance indicates that plasma transport is predominated by anomalous transport. However, the observed anomaly shows correlation with the change of an effective helical ripple ε_{eff}. Since ε_{eff} should not be directly linked with anomalous transport model, clarification of configuration dependent parameter to bridge anomalous transport and ε_{eff} is required for establishment of optimization scenario of magnetic configuration. In this study, the poloidal viscous damping rate is explored as a potential key parameter. Generally speaking, zonal flows are generated efficiently in the configuration with low poloidal viscosity and then suppression of anomalous transport is anticipated in such a configuration. Since the poloidal viscous damping rate C_p is affected by a toroidal curvature as ε_{eff} describes, C_p and ε_{eff} generally have a correlation. Indeed, the inward shift of the magnetic axis realizes suppression of both C_p and ε_{eff} simultaneously. However, plasma elongation can separate these two effects. Here elongation is defined by the toroidal averaged value. A vertically elongated configuration (κ=1.4) has larger ε_{eff} than the standard configuration (κ=1.0) while it has smaller C_p. The experimental results indicate that the confinement is the best at κ=1.0 and declined by the both prolate (κ=1.4) and oblate (κ=0.8) modifications. The present experimental comparison suggests a negative evidence for relevance of C_p.

References

[1] H.Yamada et al., Plasma Phys. Control. Fusion **43**, A55 (2001)

[2] H.Yamada et al., Nucl Fusion **41**, 901 (2001)

[3] U.Stroth et al., Nucl .Fusion **36**, 1063 (1996)

[4] H.Yamada et al., Fusion Sci. Tech. **46**, 82 (2004)

[5] H.Yamada et al., Nucl. Fusion **45**, 1684 (2005)

[6] A.Dinklage et al., Nucl. Fusion **47**, 1265 (2007)

[7] T. Kobuchi et al., Plasma Phys. Control. Fusion **48** (2006) 789.

[8] C.D.Beidler et al. Plasma Phys. Control. Fusion **36**, 317 (1994)