J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 579–583

Remarks on Saturation of Energy Confinement in High Density Regime on LHD

YAMADA Hiroshi[1], MORITA Shigeru, MURAKAMI Sadayoshi, MIYAZAWA Junichi, SAKAMOTO Ryuichi, SAKAKIBARA Satoru, WATANABE Kiyomasa, TANAKA Kenji, NARIHARA Kazumichi, OSAKABE Masaki, PETERSON Byron, NAKAMURA Yukio, GOTO Motoshi, SUZUKI Hajime and LHD Experimental Group

National Institute for Fusion Science, Toki 509-5292, Japan

[1] Concurrent post of Department of Fusion Science, School of Mathematical and Physical Science,Graduate University for Advanced Studies, Hayama, 240-0193, Japan

(Received: 11 December 2001 / Accepted: 11 June 2002)

Abstract

A study on energy confinement times in currentless helical plasmas has indicated a preferable density dependence like $\tau_E \propto \bar{n}_e^{0.5-0.6}$. However, saturation of energy confinement time has been often observed during the density ramping-up phase by gas puffing in NBI heated plasmas in LHD. The power balance analysis indicates that the thermal diffusivity is improved by the increase in local density while the global energy confinement time loses the dependence on the density. The flat or hollow density profile, which is distinguished in the density-ramping phase, promotes a broad heat power deposition. This change explains the apparent contradiction between the density dependence of the thermal diffusivity and the global energy confinement time. This result suggests that central heating can maintain a favorable density dependence of the energy confinement time in the high density regime.

Keywords:

energy confinement time, high density regime, LHD, thermal diffusivity, power balance

1. Introduction

Clarification of energy confinement times has been the most important issue in magnetic fusion research. An experimental study on energy confinement times in currentless helical plasmas has indicated a preferable density dependence like $\tau_E \propto \bar{n}_e^{0.5-0.6}$ [1]. High density operation leading to good confinement and high beta would be a merit in consideration of a reactor.

There exist, however, two kinds of density limit in magnetic confinement. One is the operational limit where the plasma collapses. The other is the performance limit beyond which confinement is degraded. The Greenwald density limit [2] is widely accepted as the operational limit in tokamaks. In contrast to tokamaks, the operational limit in helical systems is determined by the destruction of power balance [3].

The degradation or saturation of energy confinement has been reported in many experiments. Transition from linear Ohmic confinement to saturated Ohmic confinement, back transition from H-mode to L-mode, and L-mode itself are typical examples observed in tokamaks [4]. Although the positive density dependence of the energy confinement time has been recognized widely in helical systems, several experimental observations indicating saturation have been reported [5,6] as well as in tokamaks.

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

The Large Helical Device (LHD) is a large heliotron with the nominal major and minor radii of 3.9 m and 0.6 m, respectively. Experiments in LHD have extended the parameter regimes of currentless helical plasmas significantly. The favorable density dependence has been verified in much lower collisionality and higher beta regimes than the medium sized experiments [7,8]. Since the experience in tokamaks suggests that saturation of confinement is related to low heating power density [4], LHD is a good platform to investigate this issue because of its large volume.

The saturation of energy confinement time has been often observed in the density ramping-up phase in NBI-heated plasmas in LHD. The cause and the mechanism of this phenomenon are discussed in this paper.

2. Experimental observations

The performance of the energy confinement is discussed with ISS95 scaling [1] which has $\tau_E \propto \bar{n}_e^{0.51}$. The plasmas studied here employ the magnetic configuration with the magnetic axis of 3.6 m which has the best performance [7]. Figure 1 shows the change of stored energy in the density scan with almost constant absorbed heating power. Since the heating power is constant, the stored energy in the ordinate is equivalent to the energy confinement time. The stored energy evolves along the prediction of ISS95, however, gas fueled discharges show deterioration around 3×10^{19} m^{-3}. In this situation, plasma can be heated up by turning off the gas puff, which is called "reheat". After turning off the gas puff, the saturated stored energy increases again. Also pellet injection greatly extends the favorable confinement characteristics in the high density regime.

Saturation of confinement is distinguished in the density ramping-up phase (see Fig.2). The energy confinement is derived from the stored energy measured by the diamagnetic loop and the absorbed heating power estimated from the direct measurement of the shine-through power [9] and the Monte-Carlo calculation [10]. The line averaged density is doubled from t = 1.5 s to 4.0 s, however, the stored energy and the energy confinement time do not change. The improvement factor on ISS95 is degraded from 1.6 to 1. The ratio of the radiation power to the absorbed power increases from 16 % to 22 %. Although temperatures decrease

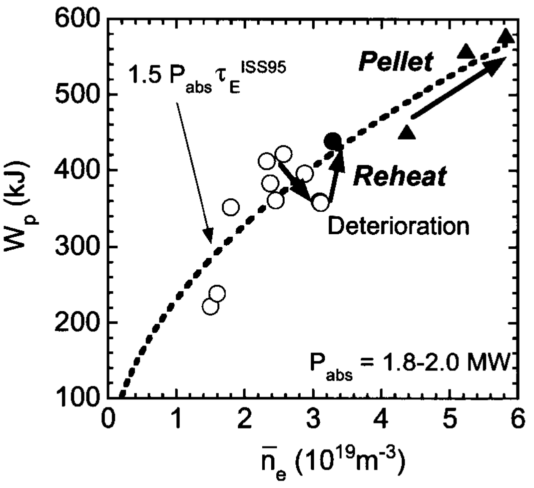

Fig. 1 Dependence of stored energy on line averaged density in the scan with fixed heating power. Open circles: gas-fueled discharge. Solid circle: reheat mode. Solid triangles: pellet-fueled discharge.

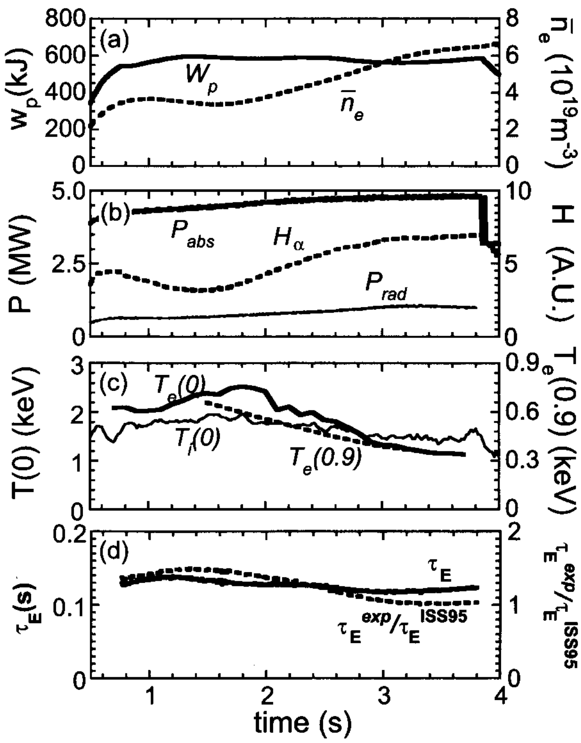

Fig. 2 Waveforms of the discharge with density ramping-up. The working gas is hydrogen. (a) Stored energy and line averaged density. (b) Absorbed power of NBI with the accelerating voltage of 111–136 keV, total radiation power, and H_α emission. (c) The electron temperatures at the center and ρ=0.9 measured by the multi-channel Thomson scattering system, and the ion temperatures measured by the crystal spectrometer (Ti XXI). (d) Energy confinement time and improvement factor on ISS95.

with the increase in density, the ratio of decrease of electron temperature is more distinguished in the center than in the edge. Ion temperature is reduced more gradually because of stronger equi-partition of energy with electrons in the higher density regime.

3. Local heat transport analysis

Based on profile measurements (electron temperature by Thomson scattering, density by multi-chord FIR interferometer [11], radiation power by bolometer array [12]), the power balance is analyzed to discuss the local heat transport. Since ion temperature profile is not available routinely, the condition of $T_e=T_i$ is assumed which can be justified in the density regime studied here. The effective thermal diffusivity $\chi_{\rm eff}$ is defined by $\chi_{\rm eff}(\rho)=-P_{cond}(\rho)/(V'(\rho)<(\nabla\rho)^2>n_e(\partial T_e/\partial\rho))$, where ρ, $P_{cond}(\rho)$, $V'(\rho)$ and $<(\nabla\rho)2>$ are the normalized minor radius, the power flow across surface ρ due to ion and electron heat conduction, the radial derivative of the specific volume and the flux surface average of $(\nabla\rho)^2$, respectively.

Figure 3 shows the power balance at t = 3.5 s of the discharge illustrated in Fig.2. Heat conduction is a primary loss channel and radiation power does not play an essential role.

The density profile is usually flat and sometimes hollow in LHD. This broad density profile is emphasized in the density ramping-up phase fueled by gas puffing (see Fig.4(a)). The drop in the temperature profile is pronounced in the central region. All 3 NBI lines are arranged for tangential injection and aligned with the tangent radius of 3.7 m, which is not optimized to the configuration with the magnetic axis of 3.6 m discussed here. As Figs.4(b) and (c) indicate, therefore, the significant power is deposited in the peripheral

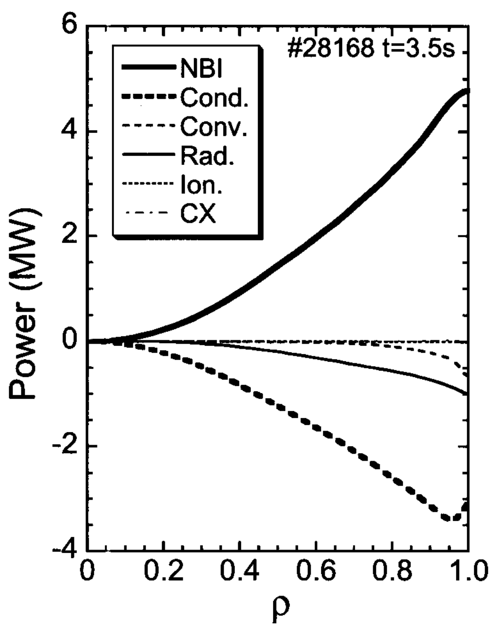

Fig. 3 Power balance at 3.5 s in the discharge illustrated in Fig.2. Input heating power is due to NBI. The major loss channel is conduction. Radiation and convection follow it. Ionization and radiation loss by neutrals (denoted by Ion), and charge exchange loss (denoted by CX) are negligible.

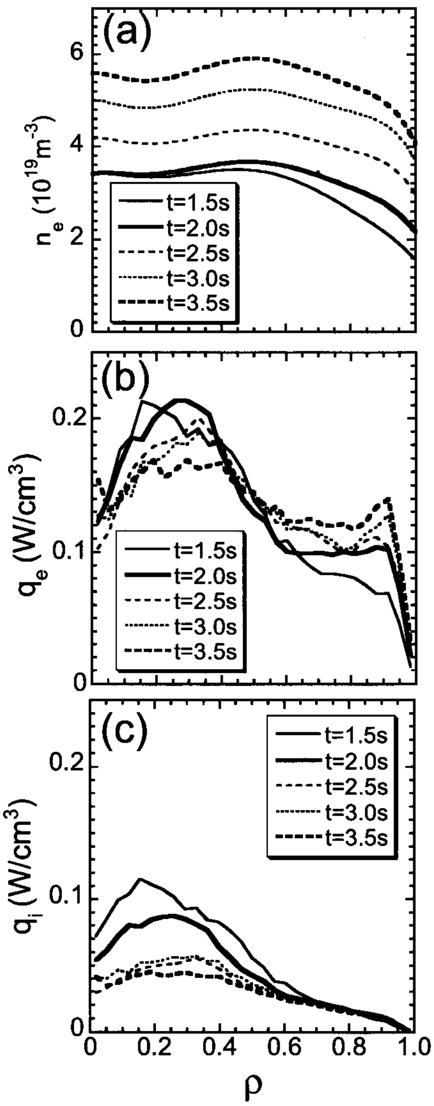

Fig. 4 (a) Electron density and heat deposition profile of NBI power at 5 times of interest in the discharge illustrated in Fig.2. (b) Power deposition to electrons. (c) Power deposition to ions.

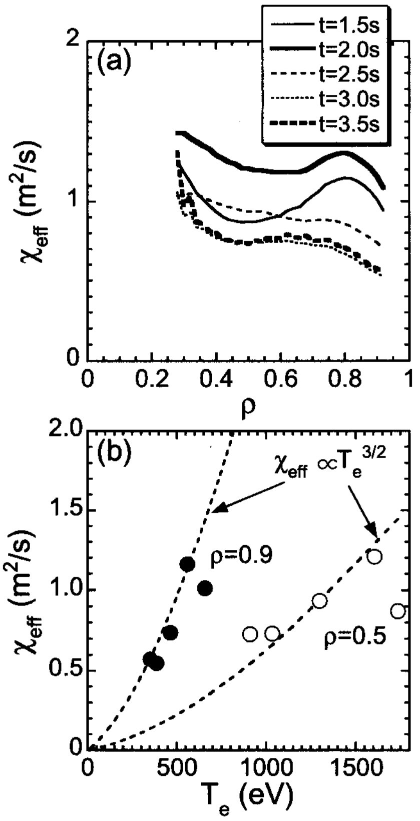

Fig. 5 a) Radial profile of thermal diffusivity. (b) Temperature dependence of thermal diffusivity at two radii of ρ=0.5 (open circles) and ρ=0.9 (solid circles).

region along with the increase in density, and consequently the power deposition profile becomes very broad.

The thermal diffusivity χ_{eff} decreases with the increase of density (see Fig.5(a)). The reduction is less in the central region although the decrease of central temperature is more pronounced than in the edge. The dependence of χ_{eff} on density can be re-expressed into a dependence on temperature as in Fig.5(b). χ_{eff} increases with the increase of the electron temperature, which seems to follow $T_e^{3/2}$.

4. Discussions

A number of studies of anomalous transport has indicated that the thermal diffusivity is proportional to $T_e^{3/2}$ which is known as gyro-Bohm transport. If the simple derivation of $\tau_E \propto a^2/\chi$ is correct, the relation of $\chi \propto T_e^{3/2}$ turns out to be $\tau_E \propto (n/P)^{0.6}$. The confinement analysis in the previous section indicates that the reasonable dependence of the thermal diffusivity on temperature is maintained while the global energy confinement does not show a density dependence. This apparent inconsistency is resolved by the significant change of the power deposition profile. If the heat transport and the total heating power are the same, the peaked heating profile gives a larger stored energy than the broad heating profile. The recovery of the intrinsic density dependence by pellet injection can be qualitatively explained by this mechanism.

The saturation of the energy confinement time in the density regime can be improved by turning off the gas puffing (reheat mode [5]). In this phenomena, the increase of the edge temperature contributes to the improvement of the energy confinement time. This dynamical enhancement cannot be explained fully by the change of the heat deposition. Precise quantitative argument is required to clarify what plays a predominant in the confinement improvement in the reheat mode as well as pellet fueled discharges.

5. Conclusions

The loss of favorable density dependence of the energy confinement time is often observed in the density ramping-up phase fueled by gas-puffing. In contrast to the global energy confinement time, the thermal diffusivity shows a reasonable density and temperature dependence. This apparent contradiction is explained by the broadening of the power deposition. The consequence suggests that central heating can maintain a positive density dependence of the energy confinement time in the high density regime, which provides a favorable prospect for current-less helical plasmas.

Acknowledgement

The authors gratefully acknowledge the effort of the device engineering group to operate LHD.

References

[1] U.Stroth *et al.*, Nucl. Fusion **36**, 1063 (1996).
[2] M. Greenwald *et al.*, Nucl. Fusion **28**, 2199 (1988).
[3] S. Sudo *et al.*, Nucl. Fusion **30**, 11 (1990).
[4] As a review, F. Wagner and U. Stroth, Plasma Phys. Control. Fusion **35**, 1321 (1993).
[5] S. Morita *et al.*, in Plasma Physics and Controlled Fusion Research (*Proc. 14th Int. Conf.*, Wuerzburg, 1992) IAEA, Vienna, Vol.2 (1993) p.515.
[6] U. Stroth *et al.*, Physica Scripta **51**, 655 (1995).
[7] H. Yamada *et al.*, Nucl. Fusion **41**, 901 (2001).
[8] H. Yamada *et al.*, to be published in Plasma Phys. Controll. Fusion.

[9] M. Osakabe *et al.*, Rev. Sci. Instrum **72**, 590 (2001).

[10] S. Murakami *et al.*, 1995 Trans. Fusion Technol. **27**, 256 (1995).

[11] K. Kawahata *et al.*, Rev. Sci. Instrum **70**, 707 (1999).

[12] B.J. Peterson *et al.*, *in Proc. 26th European Physical Society Conference on Controlled Fusion and Plasma Physics* (Maastricht, Netherlands, 1999) p3.104.