J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 109–112

Study of Toroidal Currents in LHD and Its Application to Equilibrium Control

SAKAKIBARA Satoru*, WATANABE Kiyomasa, YAMADA Hiroshi, MURAKAMI Sadayoshi, NARIHARA Kazuto, TANAKA Kenji, IDA Katsumi, KADO Shinichiro, YAMADA Ichihiro, PETERSON Byron, KOMORI Akio, KUBO Shin, MOTOJIMA Osamu and LHD Experimental Group
National Institute for Fusion Science, Toki-shi 509-52, JAPAN

(Received: 18 January 2000 / Accepted: 27 June 2000)

Abstract

Net toroidal currents of up to 60 kA have been observed in NBI plasmas of LHD. Time development of toroidal currents observed in balanced NBI plasmas have been analyzed for the identification from a viewpoint of bootstrap current. The results suggest that observed currents are quantitatively consistent with the theoretical model. The active control of the current profile using NBI is valid for improvement of destabilization of MHD modes due to bootstrap current.

Keywords:

bootstrap current, MHD equilibrium, current profile control, ideal interchange mode

1. Introduction

In helical devices, net toroidal currents are not required to produce magnetic field for plasma confinement, while theoretical prediction suggests that there are several kinds of toroidal currents, that is, bootstrap currents, beam driven currents and microwave driven currents. Even if these toroidal currents are sufficiently small to activate current driven instabilities, they can affect the characteristics of the magnetic configurations. The toroidal currents with direction increaing the rotational transform lead to the decrease in the magnetic shear and the suppression of Shafranov shift which restrains the formation of magnetic well. This improves the particle confinement due to neoclassical ripple transport, while interchange mode is destabilized [1]. Also, the reduction of magnetic shear may lead to extension of magnetic island.

Neoclassical bootstrap current has been theoretically investigated in LHD and it suggests the flow in the paramagnetic direction with the increase in rotational transform [2]. Therefore, an understanding of characteristics of toroidal currents and an optimization of MHD equilibrium by active control of current profiles are hoped for realization of steady state operation in LHD.

In this study, an identification of observed toroidal currents have been performed from a viewpoint of bootstrap currents. A technique of optimization of current profiles is also discussed.

2. Experimental Setup

The LHD is a heliotron device with l = 2 and a field period of M = 10 superconducting helical coils [3]. The major and minor radii are 3.9 m and 0.65 m, respectively. The magnetic field is excited in a steady state using superconducting coils and set at up to 2.9 T. The applied voltage is extremely low.

The net toroidal current I_p and plasma stored energy W_p are measured with Rogowski coils and diamagnetic loops installed inside the vacuum vessel, respectively. The line averaged electron density n_e is

*Corresponding author's e-mail: sakakis@LHD.nifs.ac.jp

obtained by the measurements with a 13-channels far infrared laser interferometer. The electron temperature profile is measured with the multi-channel Thomson scattering system and the temporal evolution of T_e is taken every 0.02 sec.

3. Observation of Toroidal Current

Figure 1 shows n_e dependence of I_p and W_p in NBI plasmas of R_{ax} = 3.6 m and 3.75 m configurations. The toroidal magnetic field B_t ranges from 1.5 to 2.75 T and hydrogen gas is supplied by gas puff and/or pellet injection. Data points for n_e and I_p are taken at the time when W_p is the maximum in this figure, and W_p ranges from 20 kJ to 780 kJ.

The I_p of –20 ~ 60 kA has been observed in the n_e range of less than 8×10^{19} m^{-3}, where the positive sign of I_p means the co-direction. These currents change the central rotational transform by –30 ~ 60% if the current profile is assumed as $j = j_0\,(1 - \rho^2)$. The fact that most of observed currents flow in the co. direction is consistent with bootstrap currents predicted to flow in the paramagnetic direction. The envelope of absolute value of I_p gradually increase in the density range of less than 2×10^{19} m^{-3} and decrease in high density regime. The loss of high energy particle due to the shinethrough is large in the low density regime, and it leads to decrease Ohkawa current. On the other hand, the plasma energy is dominated by the density rather than the temperature as shown in Fig. 1 (b), and the collisionality increases with the density. It makes slowing down time short and leads to degradation of efficiency of the Ohkawa current. Also, bootstrap current decreases with the collisionality.

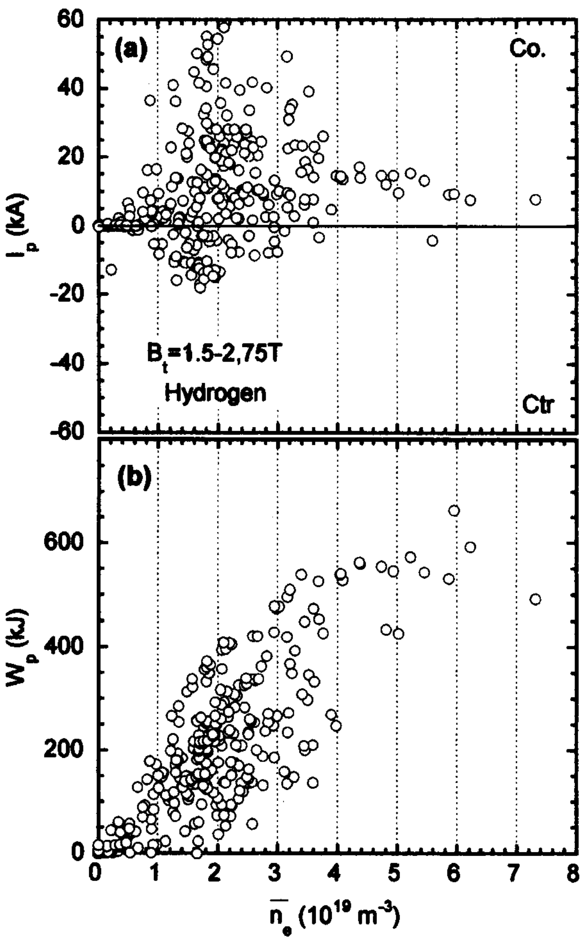

Fig. 1 Changes of (a): observed net plasma currents and (b): stored energy as a function of averaged density in NBI plasmas.

Observed currents are still in transitional state because the discharge time is too short to ramp the full currents. Therefore, an analysis for time evolution of plasma currents is required for accurate comparison with a neoclassical theory. The noninductive plasma current I_b is estimated by the following expression:

$$I_p + L_p / R_p \cdot \mathrm{d}I_p/\mathrm{d}t = V_{loop} / R_p + I_b$$

where L_p is the inductance of plasma, and R_p is the resistance estimated by a neoclassical theory. The V_{loop} is one-turn voltage and assumed as V_{loop} = 0. The density

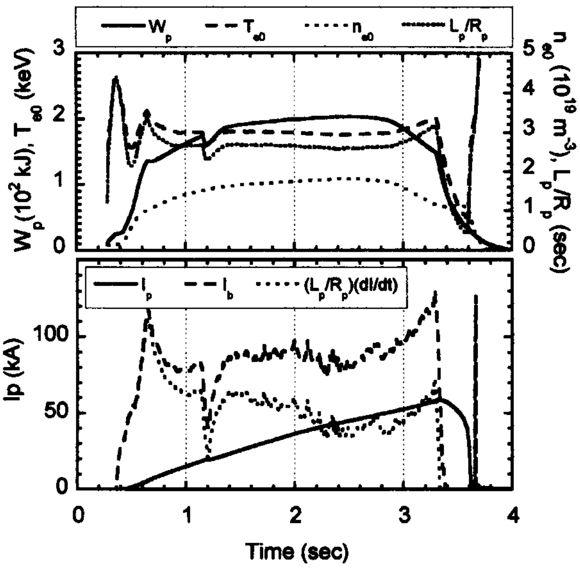

Fig. 2 Time behavior of stored energy, central electron temparature, central density, plasma current and noninductive current estimated in blanced NBI discharge.

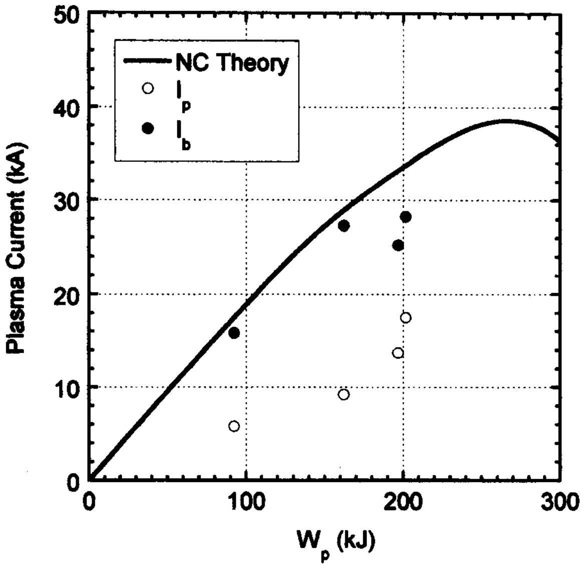

Fig. 3 Comparison of observation results and theoretical model of bootstrap current.

and temperature profiles are assumed as $n = n_0 (1 - \rho^8)$ and $T = T_0 (1 - \rho^2)$, respectively.

The analysis for time evolution of I_p in typical discharge with neutral beam balanced injection are shown in Fig. 2. Two NBI have almost the same power of Pthrough = 1.7 MW. When W_p keeps the flat top with 210 kJ during 1.4 sec from t = 1.5 sec, n_{e0} and T_{e0} also have constant value. The L_p/R_p time is about 2.7 sec in this phase. The I_p continues to ramp up during the discharge, and starts to decrease when NBI is turned off at t = 3.35 sec. The I_b of about 85 kA in the flat top phase is estimated.

Figure 3 shows the comparison between the above-mentioned I_b and theoretical model of bootstrap currents in R_{ax} = 3.75 m and B_t = 1.5 T configuration. Bootstrap current is estimated by using SPBSC code [2]. The Ohkawa current is cancelled out by balanced injection. The pressure profile is assumed as $P = P_0 (1 - \rho^8)(1 - \rho^2)$. The open and closed circles are observed I_p and estimated I_b, respectively. The I_b is well consistent with theoretical prediction.

4. Discussion

Observed currents are in transient state so far because the present discharge time is shorter than the L_p/R_p time. When steady state plasmas with high plasma pressure are realized, the excitation of large toroidal currents, which may affect MHD characteristics, is predicted. Bootstrap current makes equilibrium beta limit higher due to reduction of Shafranov shift in R_{ax} inward shifted configuration, which is mainly operated in real experiments, while it can destabilize ideal interchange modes due to suppression of well formation. Therefore, active control of bootstrap current in steady state operation is required. Figure 4 (a) shows current density profiles of bootstrap, Ohkawa and the total currents. The Ohkawa current is produced by neutral beam counter injection in this case. The D_I and rotational transform decided by these current profiles are shown in Fig. 4 (b), where D_I is Mercier criterion and well used as an index of ideal interchange instability. In the bootstrap case, rotational transform in entire plasma except core region is higher than the currentless case, and Mercier mode is destabilized further by reduction of

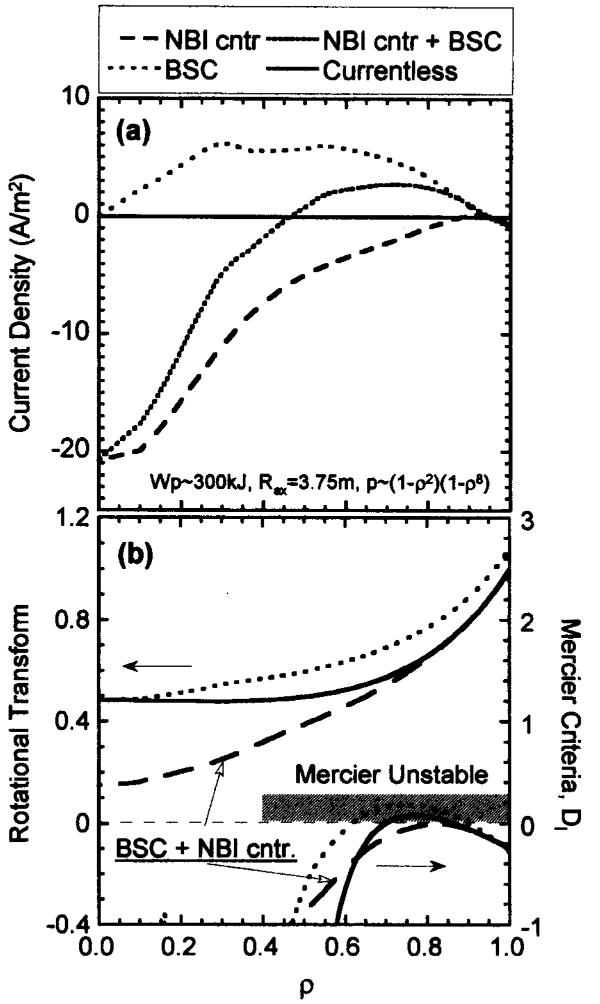

Fig. 4 (a) Current density profiles, (b): rotational transform and D_I of bootstrap, Ohkawa and the total currents.

magnetic shear.

As one of technique for making it stable, an active excitation of toroidal current may be valid [4]. By way of example, Ohkawa current excited by counter NBI is considered here. Since Ohkawa current has relatively peaked profile, it can make strong magnetic shear in the core region and ideal modes stable. The same situation may be realized by the optimization of ratio of two NBI's power.

Systematical understanding of observed toroidal currents is necessary for actual application to steady state operation.

5. Summary

Net toroidal currents of up to 60 kA have been observed in NBI plasmas of LHD. The density dependence can be qualitatively interpreted by theoretical model of bootstrap current and Ohkawa current. All of observed currents flow in the paramagnetic direction except the component of Ohkawa current. For identification of toroidal currents from a viewpoint of bootstrap current, time development of toroidal currents in balanced NBI plasmas have been analyzed because observed currents are still transient state. The results suggest that observed currents are quantitatively consistent with the theoretical model. The active control of the current profile using neutral beam injection is valid for improvement of destabilization of MHD modes due to bootstrap current. An application of this technique to steady state operation is effective.

Reference

[1] K. Ichiguchi *et al.*, Nucl. Fusion **33**, 481 (1993).
[2] K.Y. Watanabe *et al.*, Nucl. Fusion **35**, 335 (1995).
[3] A. Iiyoshi *et al.*, Nucl. Fusion **39**, 1245 (1999).
[4] T. Matsumoto *et al.*, Nucl. Fusion **36**, 1571 (1996)