Study of Toroidal Currents and MHD Equilibrium in LHD Experiment

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1.Introduction

In helical devices, net toroidal currents aren't necessary to produce magnetic field for plasma confinement. However, theoretical prediction suggests that there are several kinds of non-inductive toroidal currents, for example, bootstrap currents, Ohkawa currents and microwave driven currents. These toroidal currents aren't large enough to activate current driven instabilities. However, there is a possibility that they can affect the MHD stability and transport through changing of the magnetic configurations. The toroidal currents with direction increasing the rotational transform, we call co-direction, lead to the decrease in the magnetic shear and the suppression of Shafranov shift which restrains the formation of magnetic well. And it improves the particle confinement due to neoclassical ripple transport, while interchange mode is destabilized[1,2]. The reduction of magnetic shear may lead to extension of magnetic island, too.

Net toroidal currents of over 100kA have been observed in NBI plasmas of LHD. We have analyzed the time evolution of toroidal currents in NBI hydrogen discharges in order to identify the current driven mechanism based on the theoretical model of bootstrap current and Ohkawa current.

2.Observation of net toroidal current

The net toroidal current I_p and plasma-stored energy W_p are measured with Rogowski coils and diamagnetic loops installed inside vacuum vessel, respectively. The line integrated electron density $n_e l$ is obtained by the measurements with 13-channel far infrared laser interferometer. The electron temperature profile is measured with the multi-channel Thomson scattering system, and the time resolution is 0.02 second.

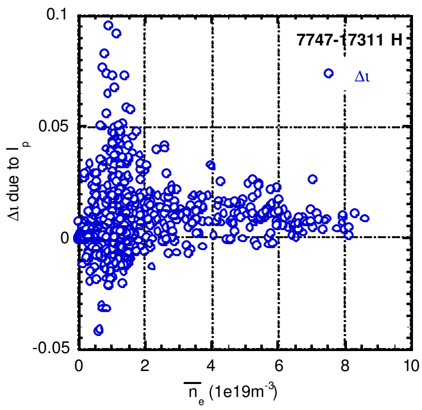

Fig.1 Dependence of Δι due to the net toroidal current on the electron density.

Figure 1 shows the increment of rotational transform, $\Delta\iota(a)$ due to maximum value of I_p as the function of n_e in NBI discharges with $R_{ax}{}^V$=3.6 m and 3.75m configurations. The toroidal magnetic field B_t ranges from 0.75 to 2.9T and hydrogen gas is supplied by gas puff and/or pellet injection. The discharge with $\Delta\iota$=-0.04~0.10, which corresponds to the I_p of -30 ~ 100 kA, has been obtained in the n_e range of less than $9\times10^{19}\mathrm{m}^{-3}$, where W_p ranges up to ~900 kJ. The $\Delta\iota$=-0.04~0.10 corresponds to the changing of the central rotational transform by -30 ~ 60 % when the current profile is assumed as $j=j_0\,(1-\rho^2)$. The positive sign of $\Delta\iota$ and I_p denotes the co-direction. $\Delta\iota$ shifts to the co-direction, and this is consistent with bootstrap currents predicted to flow in the paramagnetic direction[1]. The envelope of absolute value of $\Delta\iota$ gradually increases in the density range of less than 1×10^{19} m^{-3} and decrease in high density regime. The loss of high energy particle due to the shine-through is large in the low density regime, and it leads to decrease Ohkawa current. On the other hand, the plasma energy is contributed by the density rather than the temperature and the collisionality increases with the density. It makes slowing down time short and leads to degradation of efficiency of the Ohkawa current. Bootstrap current decreases with the collisionality, too.

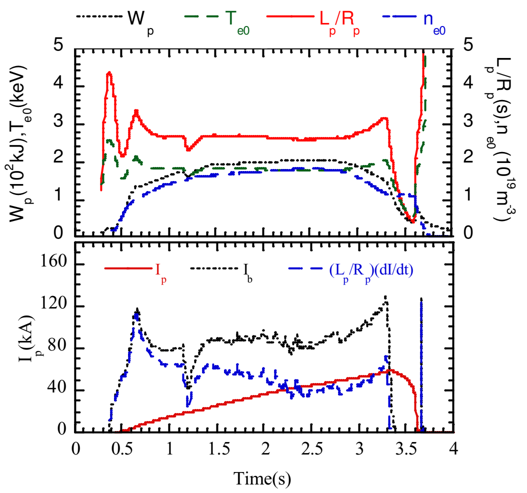

Fig.2 Time evolution of the stored energy, electron temperature, density, plasma current and non-inductive current in NBI discharge.

3. Comparison with theoretical prediction

Observed currents are still in transitional state because the typical discharge time isn't long enough for the toroidal current to be saturated. Therefore, an analysis for time evolution of plasma currents is necessary in order to compare the experimental results with a neoclassical theory. We analyze the time evolution of plasma currents by using the 0 dimensional model, here. The non-inductive plasma current I_b is estimated by the following expression:

$$I_p + L_p / R_p \cdot dI_p / dt = V_{loop} / R_p + I_b,$$

$$L_p = \mu_0 R\{\ln(8R/a) - 2\} + l_i, \quad R_p = 2\pi R / \int \sigma dS,$$

where L_p is the inductance, l_i is the internal inductance of plasma, R_p is the resistance, σ is the neoclassical conductivity and dS is the area element of poloidal cross-section. The V_{loop} is one-turn voltage and assumed as $V_{loop} = 0$. Then, it should be noticed that the saturation current, I_p(t=infinity) is equal to I_b, here. The electron temperature profile is assumed as $T_e=T_0(1-\rho^2)$. T_0 is estimated to be consistent with W_p, n_el and Thomson scattering measurements. Here, Z_{eff} is assumed as Z_{eff}=2. An analyzed result for time evolution of I_p in typical NBI discharge is shown in Fig.2. 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 balanced NBI discharge with $R_{ax}{}^V$=3.75m and B_t=1.5 T configuration. Here, Ohkawa current is cancelled out by NB balanced injection. The closed circles are the non-inductive current I_b. The open circles are the theoretical prediction of bootstrap current. The theoretical prediction of bootstrap current consistent with MHD equilibrium is calculated by using SPBSC code[3], where the electron density and temperature profiles are assumed as $n_e= n_0(1-\rho^8)$ and $T_e=T_i=T_0(1-\rho^2)$, respectively. T_0 is estimated to be consistent with W_p, n_el and Thomson scattering measurements, too.

Bootstrap current is proportional to the pressure and its gradient, mainly density gradient, in the low collisional regime[1]. In the data-set in Fig.3, the collisionalities correspond to ν_*<0.8 at ρ=0.7, then the plasmas are in the 1/ν collisional regime. The I_b dependence on W_p is consistent with that of bootstrap, that bootstrap current increases as W_p, and the I_b is quantitatively consistent with theoretical prediction, too.

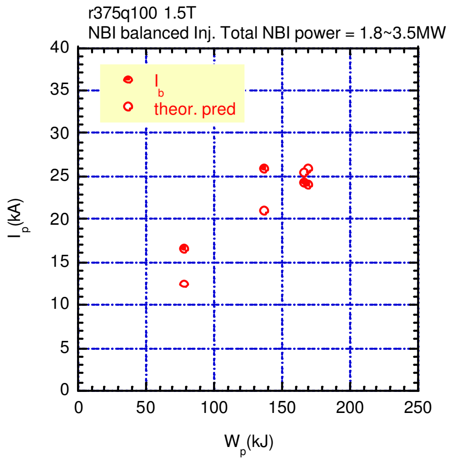

Fig.3 Comparison between non-inductive current and the theoretical prediction in balanced NBI discharges with B_0=1.5T and $R_{ax}{}^V$=3.75 configuration.

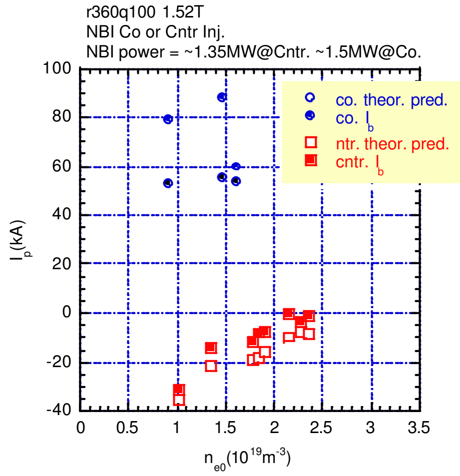

Fig.4 Comparison between non-inductive current and the theoretical prediction in co- and cntr- NBI discharges discharges with B_0=1.52T and $R_{ax}{}^V$=3.6 configuration.

Figure 4 shows the comparison between the I_b and the theoretical model in co- or cntr-NBI discharge with $R_{ax}{}^V$=3.60m and B_t=1.52 T configuration. The closed circles and squares are the non-inductive current I_b for co- and cntr- NBI discharges, respectively. The open circles and squares are the theoretical prediction of bootstrap current and Ohkawa current. The beam current is evaluated considering orbit and charge exchange losses with the three dimensional Monte Carlo simulation[4]. The geometrical factor, which is necessary to calculate Ohkawa current, is given by SPBSC code.

Ohkawa current decreases with the electron density in the regime more than a critical density. And it increases with the electron temperature. The reason is why the decrease of the electron density and increase of the electron temperature leads to the elongation of the slowing time. In Fig.4, I_b for the cntr.-NBI discharges is consistent with Ohkawa current dependence on the electron density. And the theoretical prediction coincide with the experimental results quantitatively. According to the theoretical prediction, the toroidal currents due to bootstrap current increase from ~7kA to ~15kA as the electron densities increase from $1\times10^{19}m^{-3}$ to $2.5\times10^{19}m^{-3}$. In the cntr.-NBI discharges, the theoretical prediction is consistent with experimental results quantitatively, too. In the co-NBI discharge, the theoretical model gives the smaller toroidal current comparing with experimental results.

4. Effect of Toroidal Current on MHD Equilibrium

It is well-known that magnetic axis shifts torus-outwardly due to the plasma pressure in finite beta, so called Shafranov shift. It has been observed in LHD experiments. MHD theory also predicts that net toroidal current affects the MHD equilibrium. Here we focus the magnetic axis shift in finite beta plasma with net toroidal current. Figure 5 shows the magnetic axis position in finite beta plasma with/without net toroidal current for 3 configurations, $R_{ax}{}^V$=3.60m, $R_{ax}{}^V$=3.75m and $R_{ax}{}^V$=3.90m, which is calculated by 3D MHD equilibrium calculation code, VMEC[5]. Here we assume j~$(1-\rho^2)$ as the toroidal current profile. In the high beta regime, the co-current reduces the magnetic axis shift in finite beta comparing with currentless case in all configurations. On the contrary, in the low beta regime, the co-current shifts the magnetic axis torus-outwardly. This effect is stronger as the magnetic axis is located more torus-inwardly. It is predicted that, in the $R_{ax}{}^V$=3.60m configuration with $\Delta\iota$~+0.08, the magnetic axis shifts torus-outwardly by ~5cm comparing with currentless case.

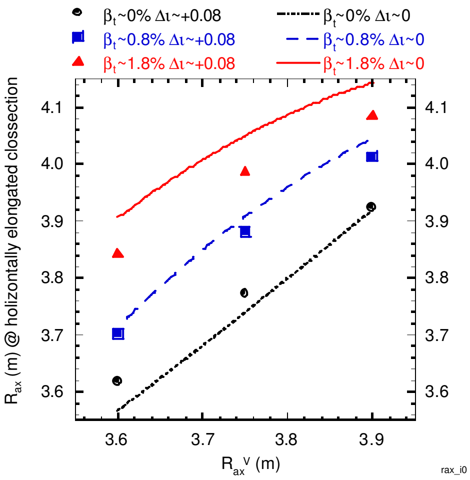

Fig.5 Magnetic axis shift in finite beta with net toroidal current for 3 configurations.

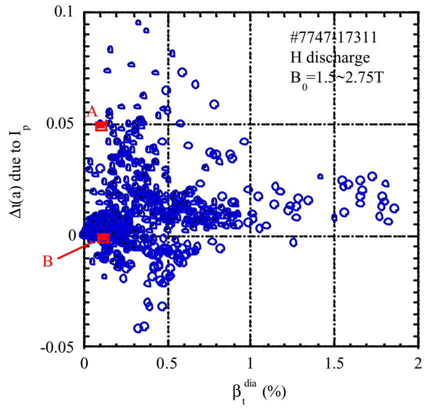

Fig.6 Operational range of Δι and volume averaged beta in LHD H discharge.

Figure 6 shows the operational range of Δι and the beta value in hydrogen discharge with B_0=1.5~2.75T up to now. LHD experiment has the discharge with Δι=-0.04~0.10 in low beta (β_t<0.4%) and Δι~0.25 in high beta (β_t~1.8%). Here β_t is the volume averaged beta. We have compared the electron temperature profile measured by Thomson scattering system in the discharges with β_t~0.1%/Δι~0.05 (A in Fig.6) and β_t~0.1%/Δι~-0.00 (B in Fig6), where the difference of magnetic axis corresponds to ~5cm according to the calculation. However, we haven't obtained the remarkable difference in the magnetic axis shifts. The high currents were obtained in long pulse discharges and/or in low density operation, when there aren't Thomson scattering data-sets enough to do the systematical study up to now.

5. Summary

In LHD NBI discharge, over 100kA net toroidal current is observed. The observed current is compared with the theoretical prediction based on bootstrap current and Ohkawa current. The theoretical model can explain the experimental results qualitatively, which corresponds to the dependence on the plasma stored energy and the electron density. However, in the low density and/or the high current discharges, the discrepancy between the experimental results and the theoretical prediction is large. In order to improve the estimation of the saturation current, the long pulse discharge or the 1 dimensional analysis of the current evolution are necessary. These are future subjects.

According to calculation results of MHD equilibrium, the net toroidal current affects the magnetic axis shift in the finite beta. However, we haven't obtained the remarkable difference in the magnetic axis shifts in Thomson scattering measurements. There is a possibility that we observe the magnetic axis shift due to the net toroidal current in low beta discharge with torus-inward magnetic axis configurations or high beta discharge with torus-outward magnetic axis configuration.

References

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