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Time evolution of toroidal currents in helical plasmas

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1. Introduction

Since the magnetic configuration which is suitable for plasma confinement are mainly produced by the external coil currents, the net plasma current is not necessary for MHD equilibria in helical plasmas in principle. So, almost all transport simulations done for LHD plasmas have neglected the net toroidal current. However, finite net plasma currents have been observed in actual LHD experiments. It is considered that the non-inductive currents, such as the bootstrap current and Ohkawa current, contribute to the net toroidal current. However, it is difficult to estimate fractions of these components accurately because plasmas are not in stationary state in many cases. In this study, time evolution of the plasma net current which is consistent to the three-dimensional MHD equilibrium is theoretically analysed by using the density and temperature profile obtained from the experimental database.

2. Non-Inductive Current

The main source of the net plasma current is considered to be non-inductive currents in helical plasmas. In the present study, we take Ohkawa current and the bootstrap current into account as non-inductive currents, and the BSC/FIT code is used to estimate these currents[1].

The blue line in Fig.1 shows a time evolution of the net toroidal current observed in an LHD discharge with two neutral beam (NB) injections. The first NB is injected to the counter-direction from $t \sim 0.7$ s and the second NB to the co direction from $t \sim 1.2$ s. Here the non-inductive current driven by the NB injection to the co-direction

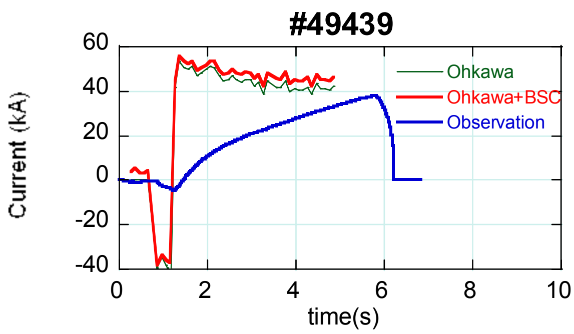

Fig.1 Time evolution of net toroidal currents in a LHD discharge with 2 NB injections.

increases vacuum rotational transform. The calculated non-inductive current is shown by the red line for both Ohkawa and bootstrap current and by the green line for Ohkawa current. In this calculation, three dimensional MHD equilibrium calculations by the VMEC code and non-inductive current calculations by BSC/FIT code are performed iteratively with time by using the density and temperature profile obtained from the experimental database. Figure 2 shows the non-inductive current profile at $t = 2.5\,\mathrm{s}$ calculated by the BSC/FIT code. Since plasma beta is low in this discharge, bootstrap current is negligibly small and Ohkawa current gives dominant contribution to the non-inductive current. Though the inductive current suppresses the rapid change of plasma current due to the non-inductive current that is introduced abruptly by the NB injection, the difference between the observed current and the calculated non-inductive current is gradually decreased with time. This fact indicates that the numerical calculation of Ohkawa current and the bootstrap current can explain the non-inductively driven current in LHD plasmas.

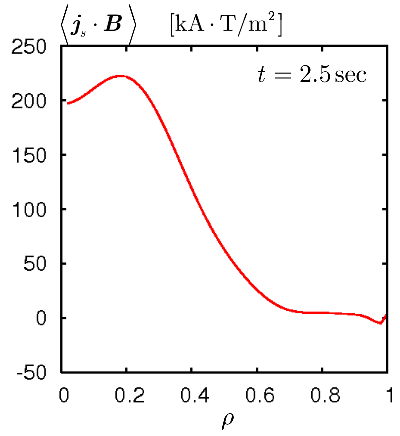

Fig.2 The non-inductive current at $t = 2.5s$ calculated by the BSC/FIT code.

3. Effect of Inductive Current

As is shown in the previous section, the net toroidal current is mainly driven by the non-inductive current such as Ohkawa current and the bootstrap current in LHD. At the same time, importance of the inductive current is demonstrated in the transient period.

The time evolution of the inductive plasma current corresponds to the resistive evolution of magnetic flux, and is posed in terms of the rotational transform ι. For the general non-axisymmetric toroidal configurations, Strand and Houlberg describe the rotational transform evolution[2]. Since the equation given by Strand and Houlberg is explicitly nonlinear equation of ι, it is considered that diffusion-type equation of the rotational transform evolution is preferable for the numerical point of view. We found in Ref.[1] that a diffusion-type equation of ι can be obtained even in the non-axisymmetric case as

$$\frac{\partial \iota}{\partial t} = \frac{1}{4\rho {\Phi_{Ta}}^2}\left[\frac{\partial}{\partial \rho}\left\{\eta_\parallel \frac{dV}{d\rho}\frac{\langle B^2\rangle}{\mu_0 \rho^2}\frac{\partial}{\partial \rho}\left[\rho\left(S_{11}\iota + S_{12}\right)\right]\right\} + \frac{\partial}{\partial \rho}\left\{\eta_\parallel \frac{dV}{d\rho}\frac{1}{\rho}\frac{dp}{d\rho}\left(S_{11}\iota + S_{12}\right) - \eta_\parallel \frac{dV}{d\rho}\frac{1}{\rho}\langle \boldsymbol{J}_s \cdot \boldsymbol{B}\rangle\right\}\right],$$

where ρ, Φ_T, V, $\eta_\parallel$, and $\langle \boldsymbol{J}_s \cdot \boldsymbol{B} \rangle$ denote radial coordinate, toroidal flux, volume inside the flux surface, resistivity, and flux surface averaged non-inductive parallel current, respectively. S_{ij} are the susceptance matrix elements[2]. Here we use the square root of the normalized toroidal flux as a radial coordinate ρ and assume total toroidal flux at the plasma boundary Φ_{Ta} to be constant in time. In this equation, $\langle B^2 \rangle$ and p' are entered instead of S_{21} and S_{22}. When we assume all the equilibrium quantities are slowly evolving quantities, we can use an implicit difference scheme like Crank-Nicholson scheme to solve this equation numerically. We use the boundary condition of $\partial\iota/\partial\rho = 0$ (at $\rho = 0$) and assume $I_T(t)$ is given at the plasma boundary.

In order to test the numerical code solving the diffusion-type equation of ι, a simulation of Ohmic current ramp-up is performed for an LHD plasma. At first, a current-free MHD equilibrium calculation is done for obtaining necessary equilibrium quantities. By using this fixed equilibrium quantities, time evolution of the rotational transform profile is calculated. Specified history of the total toroidal current is shown in Fig.3(a). Calculated time evolution of the rotational transform profile is plotted in Fig.3(b), and the corresponding net parallel current profile is shown in Fig.3(c). It is shown in Fig.3(c) that the induced plasma current diffused resistively into the core region and the parabolic stationary current density profile is obtained at $t \sim 5\,\mathrm{s}$.

Next, a simulation of the net plasma current in the presence of the non-inductive current corresponding to Fig.2 is done for the LHD discharge. As same as the Ohmic current simulation, fixed equilibrium quantities obtained from a current-free MHD equilibrium are used in the diffusion-type equation of the rotational transform. This assumption is valid if the change of the equilibrium quantities does not affect the resistive evolution of the rotational

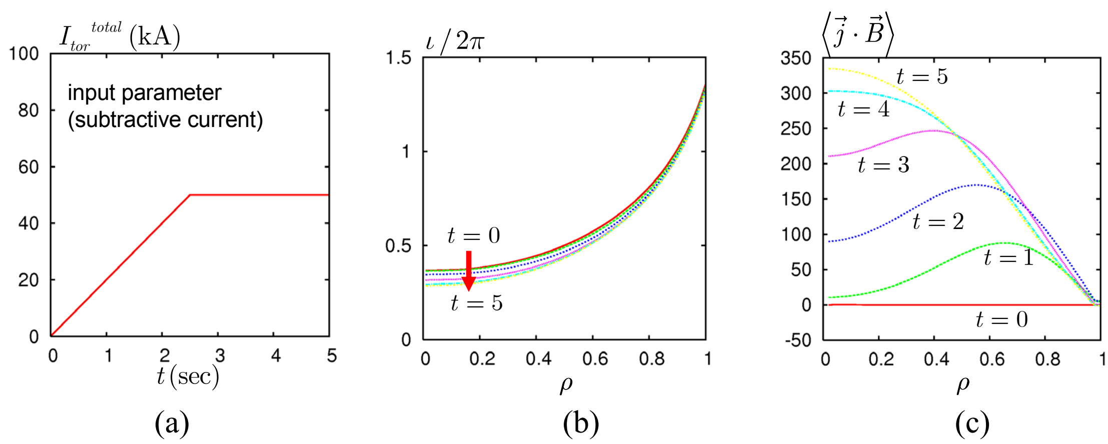

Fig. 3 Current ramp-up simulation: (a) time history of specified total toroidal current, (b) time evolution of rotational transform profile, and (c) time evolution of parrarel current density profile.

transform profile so much. Moreover, we assume that the non-inductive current profile does not change after $t = 1.5\,\mathrm{s}$, and the fixed non-inductive current shown in Fig.2 is used during the simulation.

Fig.4(a) shows time history of total toroidal current observed in the experiment. We use this time history as a specified boundary condition. The time evolutions of the rotational transform and corresponding current density are shown in Figs.4(b) and 4(c), respectively. Because of the existence of the inductive current due to the finite resistivity, the net current grows slowly and tends to the non-inductive current accompanied with the resistive decay of the inductive current with time. It takes about 5s for resistive decay of the inductive current. This result does not contradict to the experimental observation. Moreover, the calculated rotational transform profile also agrees with the experimental data by the MSE measurement.

4. Summary

Time evolution of the net plasma current which is consistent to the three dimensional equilibrium is obtained for an LHD plasma and is compared with the experimental observation. The result of the simulation seems to be consistent to the experiment. More detailed comparison requires iterative calculations of the MHD equilibrium, the non-inductive current, and the resistive diffusion of the rotational transform. This will be reported in near future.

References

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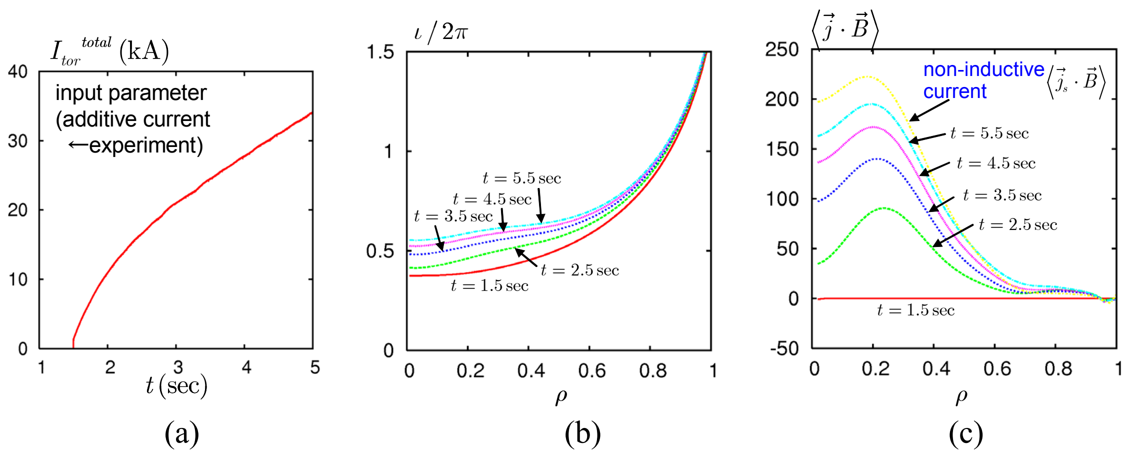

Fig.4 The results of time evolution simulation of the rotational transform and the net current in the presence of the non-inductive current in an LHD plasma: (a) time history of specified total toroidal current which is measured in the experiment, (b) time evolution of the rotational transform profile, and (c) time evolution of the net parallel current density profile.