Time-Dependent NBI-Heating Simulation of LHD Plasmas with TOTAL (Toroidal Transport Analysis Linkage) Code

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Abstract. The time-dependent simulation of neutral-beam-heated LHD plasmas has been carried out using a simulation code TOTAL (Toroidal Transport Analysis Linkage) focusing on the time evolutions of beam energy and kinetic energy. This code consists of 3-dimensional equilibrium VMEC with bootstrap currents and a 1-dimensional transport HTRANS with neoclassical loss determined by ambipolar radial electric field as well as anomalous transport. The neutral beam deposition is calculated by the Monte Carlo code HFREYA, and the slowing down process was calculated by the Fast Ion Fokker-Plank code FIFPC. The simulated time evolution of total energy including beam energy roughly agrees with the time evolution of the experimentally measured energy. The temporal change in the beam velocity distribution is also clarified.

Keywords: NBI-heating, LHD, Fokker-Plank equation, velocity distribution function, neoclassical transport, anomalous transport

1. Introduction

In order to get high temperature plasmas, neutral beam injection (NBI) heating plays an important role. Since plasma is heated due to collision with fast particle injected by neutral beam injection device, NBI scheme heats both plasma ion and electron efficiently in the future fusion reactors.

Up to now, the simulation of NBI heating in LHD experiments usually has been done in steady-state manner, and the time-dependent heating process has not been clarified in details. In this paper, we focused on the time-dependent simulation of neutral-beam-heated LHD plasma; especially, on the time evolution of kinetic energy and beam energy. In the next section, the simulation model is described. The simulation results are shown in Section 3, and the summary is given in the final section.

2. Simulation Model

In order to analyze LHD plasma heated by negative-NBI heating scheme, we have used Fast Ion Fokker-Planck Code (FIFPC) [1], which solves the slowing down process of fast ions, HFREYA code, which computes the deposition of injected neutral particle in helical plasma, and Toroidal Transport Analysis Linkage (TOTAL)[2, 3] code, which consists of 3-dimensional (3-D) equilibrium/ 1-D transport equations with both neoclassical transport and anomalous transport.

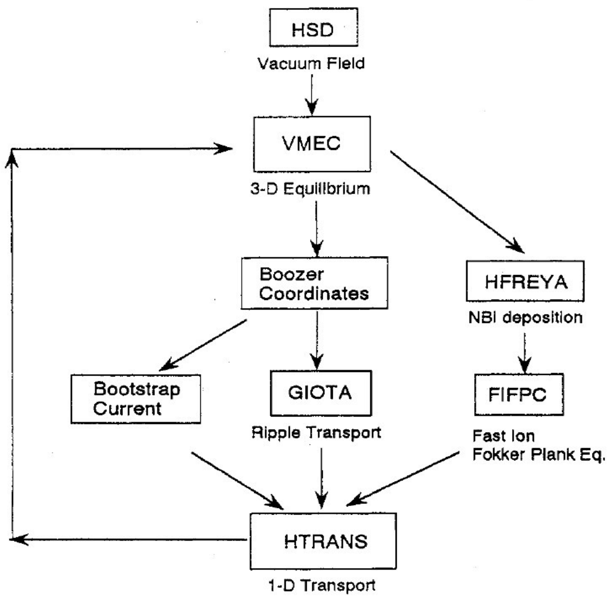

Fig.1 Schematic flow chart of the TOTAL code.

For the analysis of the LHD transport, a 2.0-D equilibrium-transport code has been developed in which the 3-D equilibrium code VMEC [4] and the 1-D transport code HTRANS are used. The NBI deposition is calculated by the HFREYA code, which is a helical modification of FREYA [5], and the slowing down calculation is done with the Fokker-Planck code

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FIFPC[1]. The anomalous transport is assumed fitted to the global experimental scaling laws ISS95 scaling law [6] with some confinement improvement factor. The schematic flow chart of this simulation code is shown in Fig. 1.

2.1.Equilibrium analysis

The initial vacuum magnetic surface is calculated by the magnetic tracing code HSD [7] with carefully arranged multi-filament currents. In the paper, the free boundary version of VMEC is used. The FCT and Boot-strap currents can be included; these currents are estimated to be not large enough to affect the present transport analysis done in this paper. The 3-D magnetic field obtained by the finite beta equilibrium of VMEC is used to evaluate the NBI heat deposition and the multi-helicity neoclassical ripple transport coefficients.

2.2. Fokker-Planck equation

To analyze this simulation, we have used FIFPC to solve the Fokker-Planck equation that describes the slowing down process of fast ions. The FIFPC may be used alone for treating neutral beam injection problems, or in combination with transport codes which describe the evolution of helical core plasma. The code is designed to calculate the fast ion distribution function in polar coordinates in velocity space at time t. The Fokker-Planck equation which yields the velocity space fast ion distribution function f(x, θ, t) is

$$\begin{aligned}\tau_s\frac{\partial f}{\partial t} &= -\frac{\tau_s}{\tau_{cx}(x)}f+\frac{1}{x^2}\frac{\partial}{\partial x}\left[\left(x^3-2Bx+x_c^3+\frac{C}{x^2}\right)f\right]\\&+\frac{1}{x^2}\frac{\partial^2}{\partial x^2}\left[\left(Bx^2+\frac{C}{x}\right)f\right]+\frac{D}{x^3}\left(1-\frac{D_1}{x^2}+D_2x\right)\\&\times\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial f}{\partial\theta}\right)+E\left(-\cos\theta\frac{\partial f}{\partial x}+\frac{\sin\theta}{x}\frac{\partial f}{\partial\theta}\right)\\&-\tau_s\frac{\dot{R}(t)}{R(t)}\left[-(1-\frac{1}{2}\sin^2\theta)x\frac{\partial f}{\partial x}+\frac{1}{2}\sin\theta\cos\theta\frac{\partial f}{\partial\theta}\right]\\&+\tau_s\sum_l \dot{n}_{f_l}S_l(x,\theta)\ ,\end{aligned}\tag{1}$$

where the terms on the right-hand side are due to charge exchange, drag, speed diffusion, angular scattering, the electric field, compression, and the source of injected fast ions, respectively. The plasma major radius, R(t), is time-dependent due to adiabatic compression which is not used here. The Spitzer slowing down time τ_s and the charge-exchange lifetime $\tau_{cx}(v)$ are given by

$$\tau_s = 120\frac{(T_e/1keV)^{3/2}}{(n_e/10^{13}cm^{-3})Z_f^2}\frac{m_f}{m_H}ms,\tag{2}$$

and

$$\begin{aligned}\tau_{cx}(v) &= \frac{6.6[1+1.1\times10^{-15}(0.5m_Hv^2)^{3.3}]}{(n_o/10^8cm^{-3})(1-0.155\log 0.5m_Hv^2)^2}\\&\times\sqrt{(\frac{25000eV}{0.5m_Hv^2})}ms,\end{aligned}\tag{3}$$

where m_f and m_H are the fast ion mass and the mass of hydrogen. B, C, D, D_1, D_2 and E are constant coefficients given in Ref.[1].

3. Simulation Results

We adopt a typical LHD discharge of the shot number 24512 [8](inward shifted configuration with magnetic axis radius R_{ax} = 3.6m;, magnetic filed strength B_0 = 1.5T) to investigate the NBI-heating process. A tangent injection beam ion energy, E_b, and beam power P_b are 142.9 keV and 4.72 MW, respectively. We have used input value of average electron density $<n_e>_{sim}$ as shown in Fig.2. This figure also shows the experimental value $<n_e>_{exp}$ and NBI power.

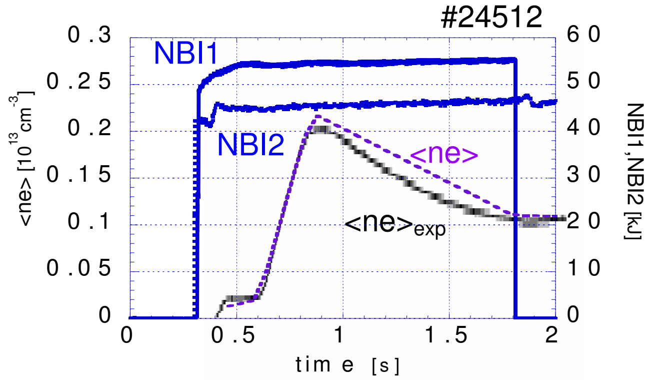

Fig.2 Experimental value of average electron density $<ne>_{exp}$ and NBI power $NBI_{1,2}$ and input value of <ne>.

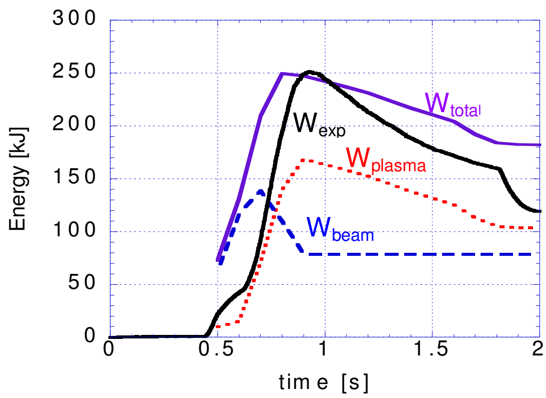

Fig.3 Time evolution of experimental and simulated beam/plasma energy in LHD.

The simulation results and typical experimental plasma energy data observed by diamagnetic coil measurement are shown in Fig. 3. In the figure, W_{total} is the summation of the simulated kinetic plasma energy, $W_{plasma} = 3nk(Te + Ti)/2$, and the beam energy, W_{beam}. In order to compare W_{exp} and W_{total} , we should define $W_{total} = W_{plasma} + fW_{beam}$, where f ~ 1/5 - 1/3. The profiles of W_{exp} and W_{total} roughly agree with each other

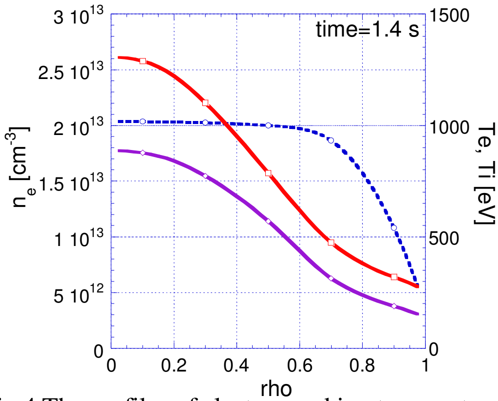

Fig.4 The profiles of electron and ion temperature and electron density at 1.4 s obtained in simulation.

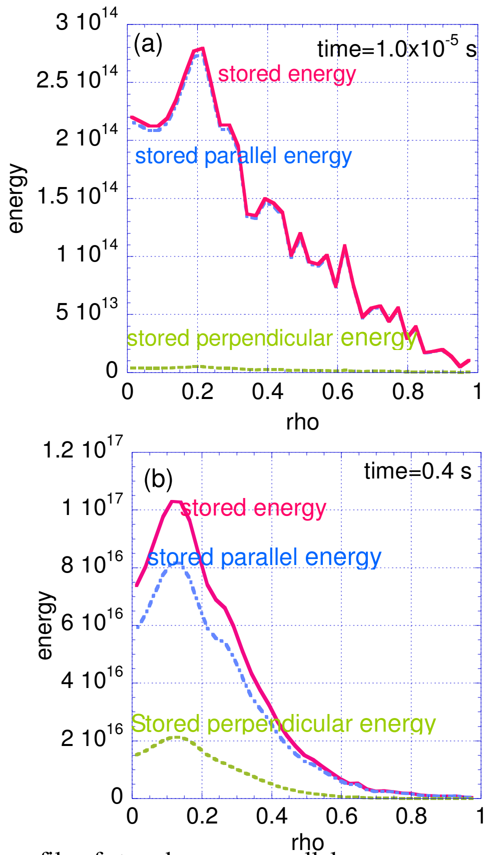

Fig.5 profile of stored energy, parallel energy component and perpendicular energy component in plasma:
(a) 1.0×10^{-5} s; (b) 0.4 s.

The Fig.4 shows electron density, n_e, and electron and ion temperature, Te and Ti, at 1.4 s. The density profile in the core is flat up to ρ=0.6. The electron temperature in plasma core is 1.4 keV, and the ion temperature is 0.9 keV.

The Fig.5 shows stored beam energy in the plasma at (a) 1.0×10^{-5} s and (b) 0.4 s. The parallel component and perpendicular component of stored energy is also plotted in Fig.5. At 1.0×10^{-5} s, the stored energy is almost parallel component energy. The perpendicular component is very low energy. At 0.4 s, the perpendicular energy increases to about a quarter of parallel energy. The beam energy is gradually transferred to various angles by diffusion and scattering process. So we investigated the distribution function in velocity space in order to analyze the details of energy transfer.

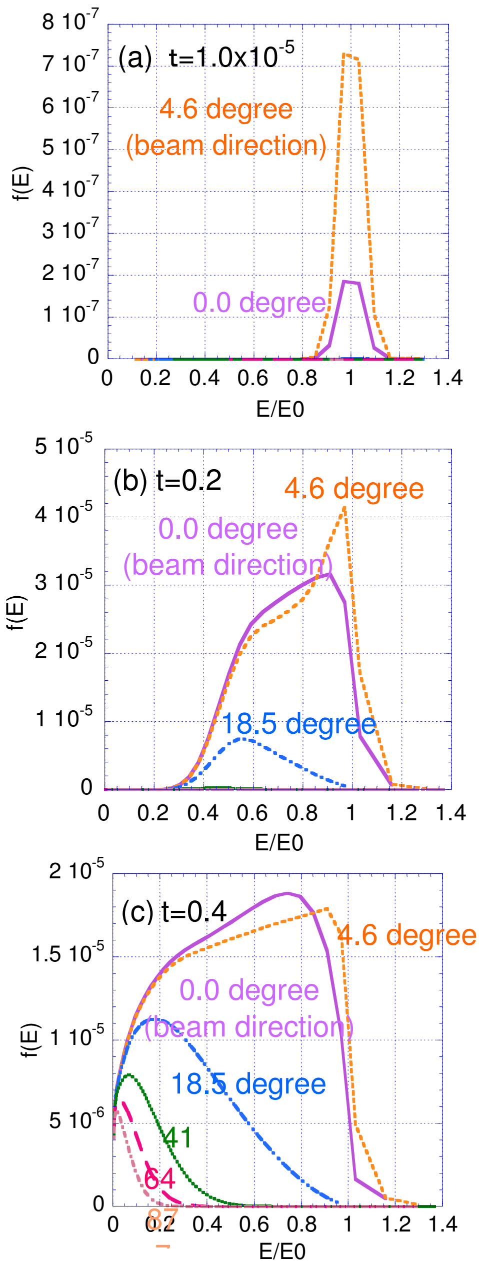

Fig.6 The distribution function of the beam ions calculated by Fast Ion Fokker-Planck Code (FIFPC);
(a) 1.0×10^{-5} s, (b) 0.2 s, (c) 0.4

The Fig.6 shows the distribution function in velocity space at ρ = 0.47. The figures (a), (b) and (c) are profiles of the distribution function at $1.0\text{x}10^{-5}$ s, 0.2 s and 0.4 s respectively. At $1.0\text{x}10^{-5}$ s, there are many ions of high energy at E/E_0=1. The beam energy is gradually transferred to high angles.

We can see from Figs. 5 and 6 that the beam consists only from the well circulating particles, and the most energetic ions are located in the plasma core.

In the code, particle orbit effects can be included by bounce average orbit in the heating process, however, this effect is not evaluated in the present simulation, because the present discharge analyzed here is the medium field, low beta operation. In the lower magnetic field and higher beta plasma case, this effect should be included.

4. Summary

We analyzed NBI-heating time-dependent process with TOTAL code. The stored energy is almost parallel component directly after injection. Later, the energy is gradually transferred to perpendicular component by diffusion and scattering process. In order to analyze the velocity distribution in detail, we used Fast Ion Fokker-Planck Code (FIFPC), which solves the Fokker-Planck equation. Directly after injection, there are many ions of high energy at E/E_0=1. Later, the high energy ion is gradually transferred to plasma core direction.

We can conclude from here that (i) the beam consists only from the well circulating particles, and (ii) the most energetic ions are located in the plasma core; there, the beam can hardly lead to edge-localized instabilities.

In summary, the time evolution of simulated total energy including beam energy roughly agrees with that of the experimentally measured energy. The temporal change in the beam velocity distribution is also clarified.

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