Integrated Heat Transport Simulation of High Ion Temperature Plasma of LHD

S. Murakami[1], H. Yamaguchi[1], A. Sakai[1], K. Nagaoka[2], H. Takahashi[2], H. Nakano[2], M. Osakabe[2], K. Ida[2], M. Yoshinuma[2], M. Yokoyama[2], A. Wakasa[1], A. Fukuyama[1] and LHD Exp Group[2]

[1]Department of Nuclear Engineering, Kyoto Univ., Nishikyo, Kyoto 615-8540, Japan
[2]National Institute for Fusion Science, 322-6 Oroshi, Toki 509-5292, Japan

Corresponding Author: murakami@nucleng.kyoto-u.ac.jp

Abstract:

A first dynamical simulation of high ion temperature plasma with carbon pellet injection of LHD is performed by the integrated simulation GNET-TD + TASK3D. NBI heating deposition of time evolving plasma is evaluated by the 5D drift kinetic equation solver, GNET-TD and the heat transport of multi-ion species plasma (e, H, He, C) is studied by the integrated transport simulation code, TASK3D. Achievement of high ion temperature plasma is attributed to the 1) increase of heating power per ion due to the temporal increase of effective charge, 2) reduction of effective neoclassical transport with impurities, 3) reduction of turbulence transport. The reduction of turbulence transport is most significant contribution to achieve the high ion temperature and the reduction of the turbulent transport from the L-mode plasma (normal hydrogen plasma) is evaluated to be a factor about five by using integrated heat transport simulation code. Applying the Z effective dependent turbulent reduction model we obtain a similar time behavior of ion temperature after the C pellet injection with the experimental results.

1 Introduction

High ion temperature, T_i, experiments have been performed applying the tangential and perpendicular NBI heating systems in LHD[2]. The high T_i plasma up to 8.1keV has been obtained during the decay phase of the density after rapid increase due to a carbon pellet injection.

It is important to analyze the confinement property of high ion temperature plasma. The high T_i plasma is obtained during the decay phase of the density after rapid increase due to a carbon pellet injection. Simple heat transport analysis of these high T_i plasma has been done but the rapid change of density effect on the NBI heat deposition and the multi-ion species effects on the heat transport is not treated accurately. In order to analyze the transport property of the time evolving plasma, we have to use NBI heat deposition analysis code including the effect of plasma time evolution. Also the plasma contains sufficient impurities due to the He gas puff and C pellet injection and the heat transport simulation should take care the multi-ion species.

In this paper we study the high T_i plasma with C pellet injection of LHD applying the integrated simulation code.We perform time-dependent NBI heating simulation of high T_i plasma of LHD using GNET-TD[3] code, which is a modified version of the 5D drift kinetic equation solver GNET[4]. We take into account the time development of the plasma density and temperature during the slowing-down of beam ions. Experimental data of the plasma density, temperature, and NBI heating is used as the input to GNET-TD. Furthermore, Next we investigate the heat transport of high T_i plasma assuming multi-ion species plasma (e, H, He, C) by the integrated transport code, TASK3D[5, 6].

2 NBI heating analysis of C-pellet injection plasma

In order to analyze the NBI heat deposition profile of time evolving plasma we have developed GNET-TD extending the 5-D drift kinetic equation solver GNET, in which the finite drift orbit and complex motion of trapped particles are included. We evaluate the distribution function of the beam ions, f_{beam}, solving the drift kinetic equation in the 5-D phase-space

$$\frac{\partial f_{\text{beam}}}{\partial t} + (\vec{v}_{\parallel} + \vec{v}_{\text{D}}) \cdot \nabla f_{\text{beam}} + \dot{\vec{v}} \cdot \nabla_{\vec{v}} f_{\text{beam}} - C^{\text{coll}}(f_{\text{beam}}) - L^{\text{particle}}(f_{\text{beam}}) = S, \tag{1}$$

where C^{coll} is the linear Coulomb collision operator, L^{particle} is the particle loss term, and S is the beam ion source term.

We performed NBI heating simulation of high-T_i discharge (# 110599) plasma, in which the plasma density changes in time due to the C pellet injection. There are five NBI injectors and one of them #4 is modulated in order to measure the ion temperature (Fig. 1-(top)). In the simulation time change of densities and temperature profiles are from the experimental measurements. The plasma density rapidly increases due to the pellet injection and decays gradually (Fig. 1). The Z_eff also increases due to the increase of the carbon impurity by the pellet injection.

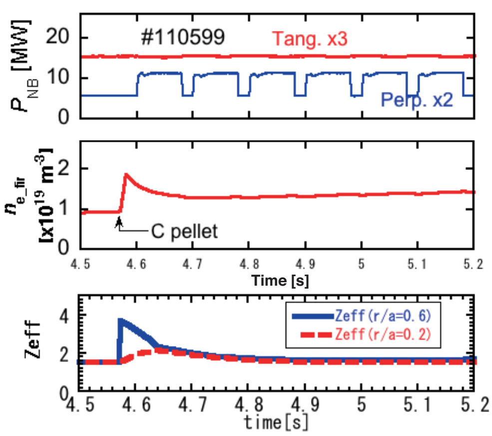

Figure 1: Time history of NBI heating power, electron density and effective charge.

GNET-TD solves a 5D drift kinetic equation including the finite drift orbit and complex motion of trapped particles. We can evaluate the time dependent beam distributions including the density and temperature time evolutions, and beam modulations. In this simulation we have assume the pure hydrogen plasma as a first step in oder to evaluate the plasma heat depositions. Also, for simplicity we assumed $Te = Ti$ because $V_{beam} >> V_i$.

We evaluate the beam distributions including time evolutions of density and temperature and beam modulations.

Before the C pellet injection beam ion distribution reaches a steady state slowing down distribution, and just after the pellet injection strong slowing down of energetic beam can be seen at the edge region. But we can not see clear change in the central region. After the density decay phase the beam ion distribution is recovered. Figure 2-(top) shows the beam ion distribution in velocity space after the pellet injection in the core region ($r/a < 0.5$). We can see the slowing down distribution of tangential (co and counter) and perpendicular injection NBI beam ions. Figure 2-(bottom) shows the NBI heat deposition in the core region ($r/a < 0.5$). The heat deposition jumps up by the pellet injection and the start of the perpendicular #4 injector at $t = 4.575$s.

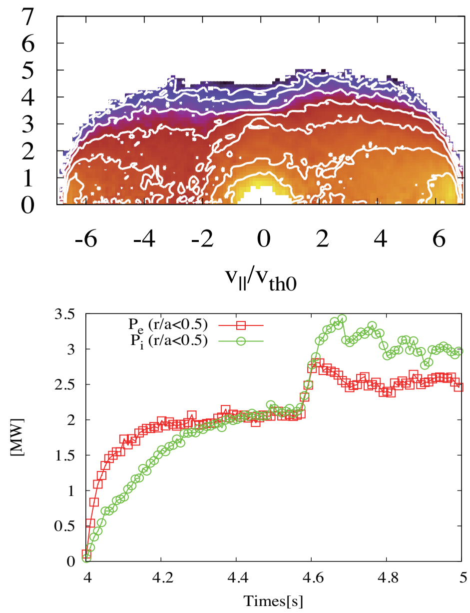

Figure 2: NBI beam ion velocity space distribution at t=4.7s (top), and time history of NBI heat deposition(bottom).

3 Heat transport simulation of high-T_i plasma

In order to perform the integrated heat transport simulation of high T_i plasma we apply the improved TASK3D code assuming multi-ion species plasma (e, H, He, C)[6]. In TASK3D one dimensional diffusive transport is solved in the TR module. The equilibrium magnet field is calculated by VMEC code and the heat source is loaded from the results of GNET-TD shown in the previous section. The heat transport model is an important part in this simulation.

The TR module solves the 1D radial diffusive transport equation for the density, the temperature and the toroidal angular momentum of each plasma species. In this study, we only consider the heat transport solving the heat transport equation in the radial ρ-direction where ρ is the normalized minor radius;

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_{\rm s}T_{\rm s}V'^{5/3}\right) = -V'^{2/3}\frac{\partial}{\partial \rho}\left(V'\left\langle|\rho|\right\rangle\frac{3}{2}n_{\rm s}T_{\rm s}V_{\rm Es}\right. \\ \left. -V'\left\langle|\rho|^2\right\rangle\frac{3}{2}D_{\rm s}T_{\rm s}\frac{\partial n_{\rm s}}{\partial \rho} - V'\left\langle|\rho|^2\right\rangle n_{\rm s}\chi_{\rm s}\frac{\partial T_{\rm s}}{\partial \rho}\right) + P_{\rm s}V'^{5/3}, \quad (2)$$

where $n_{\rm s}$ and $T_{\rm s}$ are the density and temperature of s-specifies. V is the plasma volume and $V' = dV/d\rho$.

$$V_{\mathrm{Es}} = V_{\mathrm{Ks}} + (3/2)V_{\mathrm{s}} \tag{3}$$

where V_{Ks} is the heat pinch velocity and V_{s} is particle pinch velocity. D_{s} and χ_{s} are the particle and thermal diffusion coefficient, respectively. P_{s} is the heating power source. $<>$ represents the magnetic surface average.

We assume that the thermal diffusion coefficients are given by the sum of a turbulence transport term χ^{TB} and a neoclassical transport term χ^{NC} as

$$\chi = \chi^{\mathrm{TB}} + \chi^{\mathrm{NC}}. \tag{4}$$

In this study, the particle diffusion coefficient, heat pinch velocity, and particle pinch velocity are assumed to be only neoclassical components and no contribution from the turbulent transport. Thus, V_{s} and V_{Ks} are given by

$$V_s = \frac{1}{n_{\mathrm{s}}}\left[\Gamma_s^{\mathrm{NC}} + D_1^{\mathrm{s}}\frac{\partial n_{\mathrm{s}}}{\partial r}\right], V_{\mathrm{Ks}} = \frac{1}{n_{\mathrm{s}}T_{\mathrm{s}}}\left[Q_{\mathrm{s}}^{\mathrm{NC}} + n_{\mathrm{s}}D_2^{\mathrm{s}}\frac{\partial T_{\mathrm{s}}}{\partial r}\left(\frac{D_3}{D_2} - \frac{3}{2}\right)\right], \tag{5}$$

where

$$\Gamma_{\mathrm{s}}^{\mathrm{NC}} = -n_{\mathrm{s}}D_1^{\mathrm{s}}\left\{\frac{1}{n_{\mathrm{s}}}\frac{\partial n_{\mathrm{s}}}{\partial r} - \frac{q_{\mathrm{s}}E_r}{T_{\mathrm{s}}} + \left(\frac{D_2^{\mathrm{s}}}{D_1^{\mathrm{s}}} - \frac{3}{2}\right)\frac{1}{T_{\mathrm{s}}}\frac{\partial T_{\mathrm{s}}}{\partial r}\right\}, \tag{6}$$

$$Q_{\mathrm{s}}^{\mathrm{NC}} = -n_{\mathrm{s}}T_{\mathrm{s}}D_2^{\mathrm{s}}\left\{\frac{1}{n_{\mathrm{s}}}\frac{\partial n_{\mathrm{s}}}{\partial r} - \frac{q_{\mathrm{s}}E_r}{T_{\mathrm{s}}} + \left(\frac{D_3^{\mathrm{s}}}{D_2^{\mathrm{s}}} - \frac{3}{2}\right)\frac{1}{T_{\mathrm{s}}}\frac{\partial T_{\mathrm{s}}}{\partial r}\right\}, \tag{7}$$

are the neoclassical particle flux and heat flux and D_1^{s}, D_2^{s}, and D_3^{s} are the neoclassical particle diffusion coefficient, off-diagonal term, and thermal diffusion coefficient, respectively. These neoclassical transport coefficients are determined by the DGN/LHD[7, 8] module. The radial electric field, E_r, is an important factor in the neoclassical transport coefficient. In tho study we determine E_r by the am-bipolar condition of neoclassical electron and ion fluxes as $\sum_s \Gamma_s^{NC}(E_r) = 0$.

We assume that the heat transport consists of the neoclassical transport and the turbulent transport. For the turbulent transport we assume the gyro-bohm model and the gyro-bohm gradTi model for the electron and ion heat conductions as

$$\chi_e^{TB} = C_e\left(\frac{T}{eB}\right)\left(\frac{\rho}{L}\right), \quad \chi_i^{TB} = C_i\left(\frac{T}{eB}\right)\left(\frac{\rho}{L}\right)\left(\frac{aT'}{T}\right), \tag{8}$$

where C_e and C_i are the constant factors estimated by best fitting of the hydrogen L-mode shot profile data[9]. We have investigated about twenty of pure hydrogen plasma shots and have found that the this models for electron and ion agree with the experimental results with fixed constant numbers, C_s. In the previous paper we, also, have shown that the ion and electron temperature agrees well with that of experimental results with this model in the time evolving pure hydrogen NBI heating plasma with out pellet injection [10].

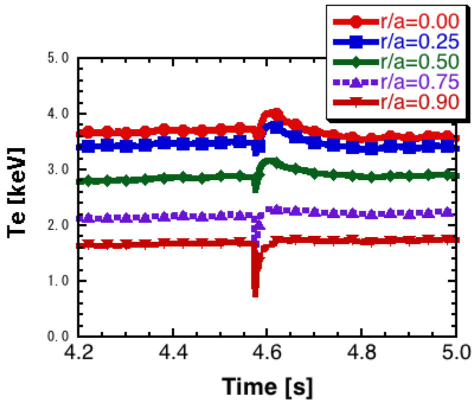

Figure 3: Time history of T_e before and after the C pellet injection.

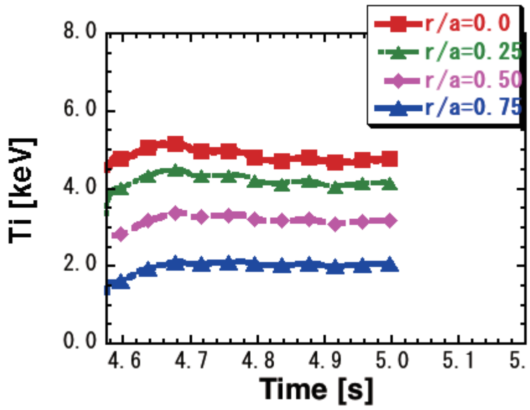

Figure 4: Time history of T_e before and after the C pellet injection.

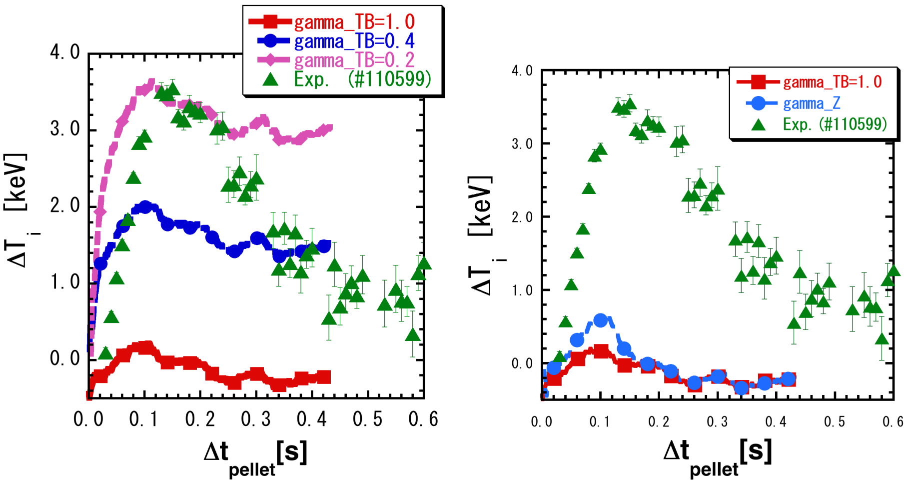

Figure 5: Time history of ΔT_i with the simple improvement model (left) and the Z_{eff} depending improvement model based on IFS-PPPL model (right).

We perform the integrated heat transport simulation of high-T_i discharge (# 110599) plasma using the density profiles from the experimental measurements. The electron temperature drops rapidly by the pellet injection at $t = 4.575$s and backed to the previous temperature(Fig. 3). This shows similar behavior with the experimental one. The ion temperature increases to more than 5 keV just after the pellet injection until $t = 4.7$s and gradually decreases (Fig. 4). This is due to the reduction of effective neoclassical transport and the decrease of the ion number density by the C-pellet injection. However the obtained T_i value is lower than that of experimental one. This indicates that the reduction of the turbulent transport is necessary to explain the observed high-T_i.

Next we introduce the confinement improvement factor, γ_{TB}, in the ion turbulent heat transport model as

$$\chi_i^{TB} = \frac{1}{\gamma_{TB}} \chi_{(L-mode)}^{TB}. \qquad (9)$$

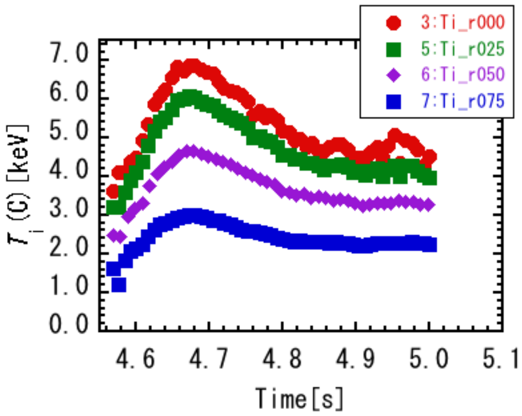

Figure 6: Time history of T_C with the Z_{eff} depending improvement model.

where $\chi^{TB}_{(L-mode)}$ is the turbulent transport model assumed in the pure hydrogen plasma. Figure 5-(left) shows the time evolution of T_i changing the improvement factor, γ_{TB}, from 1 to 5. It is found that about factor five of the improvement of the turbulent heat conduction is necessary to obtain the high T_i observed experimentally. Interestingly we see a large enhancement of negative radial electric field by changing the improving factor γ and this enhanced radial electric field reduce the neoclassical transport of ions. Increasing the γ we obtain higher T_i but the neoclassical transport value does not increase or even decreased for hydrogen ion.

It has been suggested experimentally that the C impurity is one of key factors in the ion heat transport improvement in the LHD[11]. So we consider the turbulent transport improvement model depending on Z_{eff}. The IFS-PPPL transport model[12] has included the model depending on Z_{eff}. We, first, consider the turbulent transport improving model assuming the similar Z_{eff} dependence. Figure 5-(right) shows the simulation results with the Z_{eff} depending improving model similar to the IFS-PPPL transport model. However the reduction is much smaller and we found that this model can not explain the LHD experimental results.

Then, we assume the following stronger Z_{eff} depending model as

$$\chi_i^{TB} = \gamma_Z \chi_i^{TB(L-mode)}, \qquad \gamma_Z = min1, (C_Z/Z_{eff})^{k_Z}. \tag{10}$$

Figure 6 shows the simulation results with the stronger Z_{eff} depending model ($C_Z = 1.5$ and $k_Z = 1.8$). We obtain a relatively good agreement of the ion temperature time behavior after the pellet injection with the experimental results.

4 Conclusions

We have investigated the high ion temperature plasma with carbon pellet injection of LHD applying the integrated simulation by GNET-TD+TASK3D. NBI heating deposition of time evolving plasma has been evaluated by the 5D drift kinetic equation solver, GNET-

TD and the heat transport of multi-ion species plasma (e, H, He, C) has been studied by the integrated transport simulation code, TASK3D.

It is found that the heat transport is reduced by the carbon impurity injection due to the reduce of effective neoclassical transport and the reduce of ion number density. About factor five of the turbulent transport reduction from the L-mode plasma (normal hydrogen plasma) has been indicated to achieve the high ion temperature obtained experimentally. Applying the Z effective dependent turbulent reduction model we have obtained a similar time behavior of ion temperature after the C pellet injection with the experimental results. This suggests a key role of the C impurity to reduce the ion turbulent heat transport in the high ion temperature plasma of LHD.

References

[1] NAGAOKA, K. et al 2014 Proceedings of IAEA Fusion Energy Conference PPC/2-1.

[2] TAKAHASHI, H. et al., Nucl. Fusion **53** (2013) 073034.

[3] YAMAGUCHI, H. et al., Plasma Fusion Res., **8** (2013) 2403099.

[4] MURAKAMI, S. et al., Nucl. Fusion, **46** (2006) S425.

[5] SATO M. et al., Plasma Fusion Res., **3** (2014) S1063.

[6] SAKAI, A. et al., Plasma Fusion Res., **9** (2014) 3403124.

[7] WAKASA, A. et al., Jpn. J. App. Phys. **46** (2007) 1157.

[8] WAKASA, A. et al., Plasma Fusion Res., **3** (2008) S1030.

[9] WAKASA, A. et al., Proc. 39th EPS Conf. and 16th Int. Cong. Plasma Phys., 2012, **P2.028**.

[10] YAMAGUCHI, H. et al., JPS Conf. Proc., **1** (2014) 015045.

[11] YOSHINUMA, M. et al 2014 Proceedings of IAEA Fusion Energy Conference EX/P6-30.

[12] KOTSCHENREUTHER, M. et al., Phys. Plasmas **2** (1995) 2381.