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Simulation Modeling of Impurity Transport in Toroidal Fusion Plasmas

YAMAZAKI Kozo*, AMANO Tsuneo, IGITKHANOV Yuri[1], GARCIA Jeronimo[2], DIES Javier[2], SAMITOV Marat[3] and MIKHAILOV Mhail[3]

National Institute for Fusion Science, Toki 509-5292, Japan

[1] *Max-Planck-Institut fur Plasmaphysik, IPP-EURATOM Ass., Greifswald, Germany*

[2] *Universitat Politecnica de Catalunya, Barcelona, Spain*

[3] *Russian Research Centre 'Kurchatov Institute', 123182 Moscow, Russia*

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Abstract

The impurity transport simulation code coupled with 1-D (dimensional) transport / 3-D equilibrium TOTAL (Toroidal Transport Analysis Linkage) code is developed with self-consistent ambipolar electric field due to both fuel and impurity ions. Multi-species of impurity ions are treated in the analysis of ignited fusion plasmas controlled by feedback scheme with gas/pellet fueling and heating power. The present analysis with rather low impurity contents shows that the neoclassical ripple transport flux of impurity ions is small comparing with the axi-symmetric neoclassical impurity flux. When the anomalous diffusion is introduced, this cancels the axi-symmetric neoclassical flux and makes the impurity density profile flat. This simulation code can be utilized for the impurity transport analysis of various toroidal magnetic configurations.

Keywords:

impurity transport, helical plasma, toroidal fusion reactor, magnetic configuration, radiation loss

1. Introduction

In order to access to the ignition regime of the fusion reactor, the impurity radiation loss and plasma density limit are critical, as well as the energy confinement degradation and the plasma beta limitation. The density limit might be related to the impurity radiation power loss in helical systems, and be relevant to the radiation and plasma current instability effects in tokamak systems. Moreover, to clarify the radial impurity profile, the radial energy balance is important for the access to the ignited reactor plasma. In order to clarify these issues, reactor plasma analysis was performed using the TOTAL (toroidal transport analysis linkage) code in Ref. [1]. In this paper, we include multi-species impurity dynamics with self-consistent ambipolar electric field and study the ignited plasma operation dynamics of helical reactor systems.

2. Transport models including impurity dynamics

For studying the transport of plasma fuel and impurity ions in fusion reactors, we used 2.0-D (1-D transport/3-D Equilibrium) time-dependent simulation model [2] with low-Z gas and high-Z metal impurity dynamics. The plasma density n_e, n_i and temperature T_e, T_i are described by

$$\frac{\partial n_i}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho}V'\Gamma_i = S_i, \qquad \sum_i Z_i n_i \approx n_e, \tag{1}$$

$$\frac{3}{2}\frac{\partial n_e T_e}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho}\left\{V'\left(q_e + \frac{5}{2}\Gamma_e T_e\right)\right\} = P_{He} - P_{ei} - P_{rad} - \Gamma_e E_r, \tag{2}$$

$$\frac{3}{2}\frac{\partial n_i T_i}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho}\left\{V'\left(q_i + \frac{5}{2}\Gamma_i T_i\right)\right\} = P_{Hi} + P_{ei} - P_{cx} + z_i\Gamma_i E_r, \tag{3}$$

using the normalized radius ρ and the volume V defined by the equilibrium magnetic surface. The plasma equilibria with arbitrary 3-D shapes are calculated by VMEC code [3] for tokamak and helical systems including advanced shaped stellarators [4]. The radiation loss P_{rad} is the summation of bremsstrahlung, line radiation and synchorton radiation. The present synchrotron radiation loss model was compared with non-local CYTRAN synchrotron radiation results [5], however, the energy loss is small in the present reactor model with assumed good reflection coefficients.

For the impurity dynamics, the rate equation and diffusion equation are solved using IMPDYN code [6] coupled with ADPAK atomic physics package [7],

Corresponding author's e-mail: yamazaki@ees.nagoya-u.ac.jp

* *Present address: Department of Energy Engineering and Science, Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan*

$$\frac{\partial n_k}{\partial t} = -\frac{1}{V'}\frac{\partial}{\partial \rho}(V'\Gamma_k) + [\gamma_{k-1}n_{k-1} + \alpha_{k+1}n_{k+1} - (\gamma_k + \alpha_k)n_k]n_e + S_k, \quad (4)$$

$$\Gamma_k = \Gamma_k^{NCs} + \Gamma_k^{NCa} - D_k(\rho)\frac{\partial n_k}{\partial \rho} + V_k(\rho)n_k, \quad (5)$$

with ionization rate γ_k, recombination rate α_k and particle source term S_k. The fluxes Γ_k^{NCs} and Γ_k^{NCa} are neoclassical symmetric and asymmetric ones, respectively. Here, a constant diffusion coefficeint D_k and a simple inward velocity model $V_k = V(a) \cdot (r/a)$ are adopted for anomalous impurity transport. The main fuel neutrals are calculated by the AURORA Monte Calro code [8].

The ripple transport flux Γ^{NCa} is given by the density gradient term, temperature gradient term and the radial electric field term as shown in Refs. [9,10],

$$\Gamma^{NCa} \propto D_{rip\nabla n}\nabla n/n + D_{rip\nabla T}\nabla T/T - ZE_r/T$$

The first and second terms also depend on the radial electric field.

Many elaborate works on neoclassical impurity dynamics have been done for tokamak plasmas. However, for helical systems only a few papers [11] related to impurity transport theory have been published. Here, we adopted the neoclassical formula of fuel ions to include the impurity ions in addition to the tokamak-like axi-symmetric neoclassical flux [12].

The radial electric field E_r is determined by the neoclassical asymmetric transport flux Γ^{NCa} [9,10] including impurity ions in helical system as follows,

$$\sum_k z_k\Gamma_k^{NCa}(E_r) - \Gamma_e^{NCa}(E_r) = 0. \quad (6)$$

or adding the time-derivative term of the radial electric field in the right hand side instead of zero. Here, the subscript k denotes fuel ions (deuteron & triton), helium and impurity ions.

As an input of simulation code, impurity density of each spieces is given and the time-dependent contents of these impurities are determined by their recycling rate, and diffusive and convective transport terms.

3. Simulation results

3.1 Ignited plasma of LHD-type Helical Reactor (LHR)

In the present analysis, the LHR-S (Large Helical Reactor-Standard) system [1] having $R = 16.5$ m, $B = 5$ T is adopted as a reference with H-factor based on New LHD confinement scaling models [13]. The radial profile of electron anomalous thermal transport coefficient is assumed here as $\chi \propto C(1 + k\rho^m)$ with $k = 5$, $m = 4$. The coefficient C is determined to fit the required H-factor. Here, the particle transport coefficient is modeled to be one tenth of thermal diffusivity as used in Ref. [2]. The target alpha power is 450 MW (roughly 1 GW-electric). The gas fueling and the external heating power are feedback controlled to trace the time evolution of target fusion power. The previous analysis has been given in Ref. [1] and the plasma with peaked temperature (central temperature ~ 20 keV) and flat density profile (average $1.5\times10^{20}/\mathrm{m}^{-3}$) are expected in this reactor.

3.2 Impurity transport in reactor plasmas

First, we checked the impurity profile in the LHR-S background plasma with fixed density and temperature profile, $n \propto (1 - \rho^8)$ and $T(\mathrm{keV}) = 20 \times (1 - \rho^2)^2$. The tokamak-like plasma with only symmetric neoclassical loss is analyzed as well as helical plasma transport with symmetric and asymmetric neoclassical impurity losses. In the case of carbon impurities, they are fully stripped and the behavior near the edge region is differ-

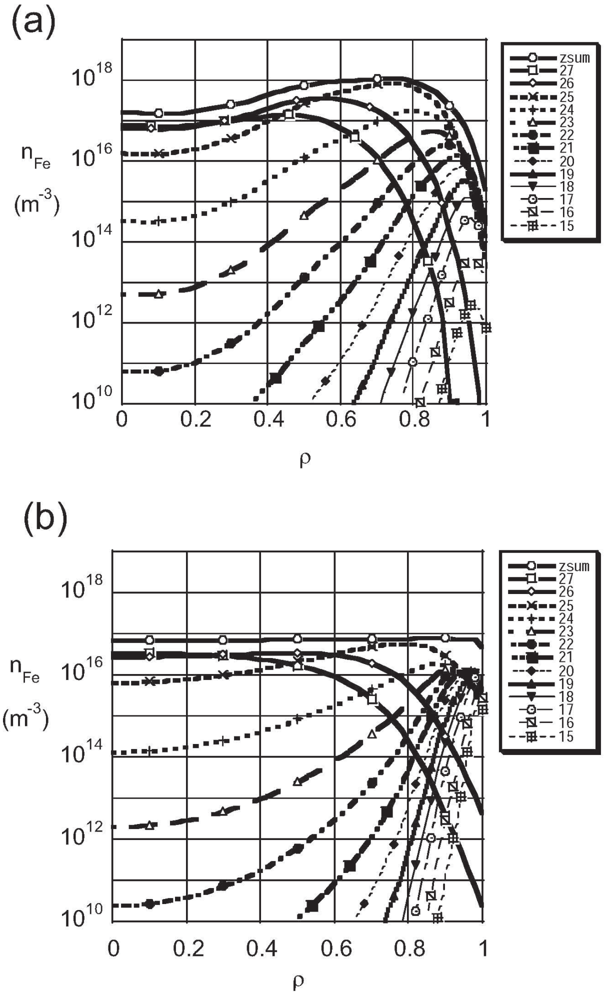

Fig. 1 Steady-state ion impurity charge-state density profiles in the LHR-S plasma with 20 keV peaked temperature and $10^{20}/\mathrm{m}^3$ flat density. (a) without anomalous transport, and (b) with constant anomalous transport ($D_{AN} = 1\ \mathrm{m}^2/\mathrm{s}$).

ent from tokamak-like transport due to strong edge electric field. The anomalous transport with $D_{AN} = 1\,\mathrm{m}^2/\mathrm{s}$ and $v(a) = 0$ flattens the impurity density profile. In iron impurity case, the maximum density was obtained for the charged state of $Z = 24$ ($k = 25$) at the radius of $\rho \sim 0.8$ (Fig. 1).

3.3 Operation dynamics of ignited LHR-S plasma with impurity ions

The radiation loss and the relevant density limitation are serious especially during the start-up phase of reactor plasmas. Here, we analyze the operational scenarios of LHR-S plasma from the low density startup to the final high-density steady-state operation of the reactor (Fig. 2). Using less than 200 MW heating power control, about 20 keV peaked temperature profile with rather flat density is expected (Fig. 3). In this operation scenario, the whole plasma is in the negative-electric-field (ion-root) regime (Fig. 3 (a)). The initial carbon and iron impurity contents in this case are 1 % and 0.1 %, respectively. Finally, the effective charge number is 1.2 ∼ 1.5, and the radiation loss related to iron density is mainly at $\rho \sim 0.8$ and near the edge (Fig. 3 (b) & 4 (b-1)). The carbon impurities are fully stripped and rather flat (Fig. 4 (a-1)). In this simulation, the anomalous term (AN in Fig. 4) compensates symmetric neoclassical term (NC_sy) (Fig. 4 (a-2) for carbon, and (b-2) for ion impurity), and the asymmetric term (NC_as) is not dominant in comparison with toroidal symmetric loss term. Only asymmetric neoclassical transport depends on the radial electric field, therefore, the effect of electric field on impurity transport is small.

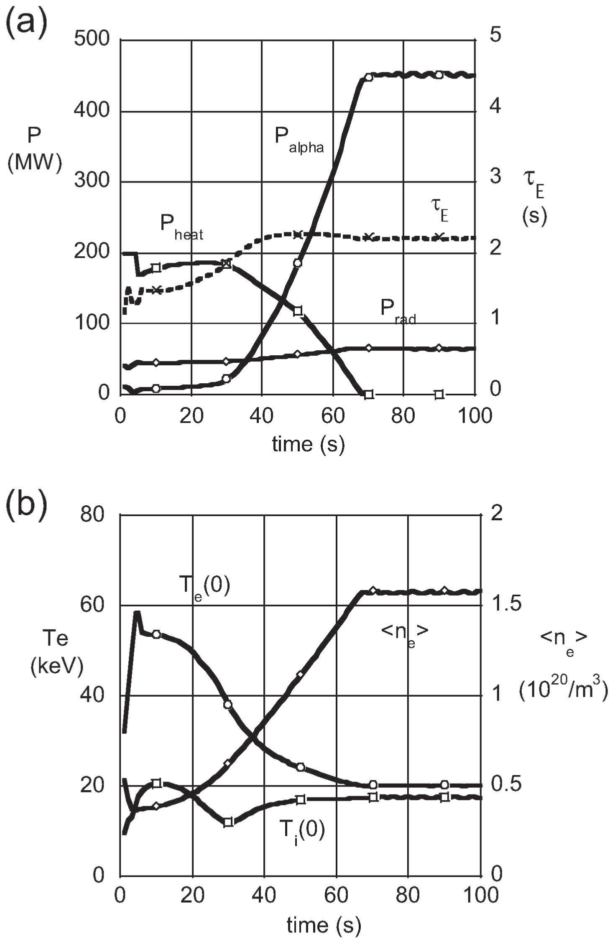

Fig. 2 Time evolution of feedback controlled LHR-S reactor plasma with impurity ions.

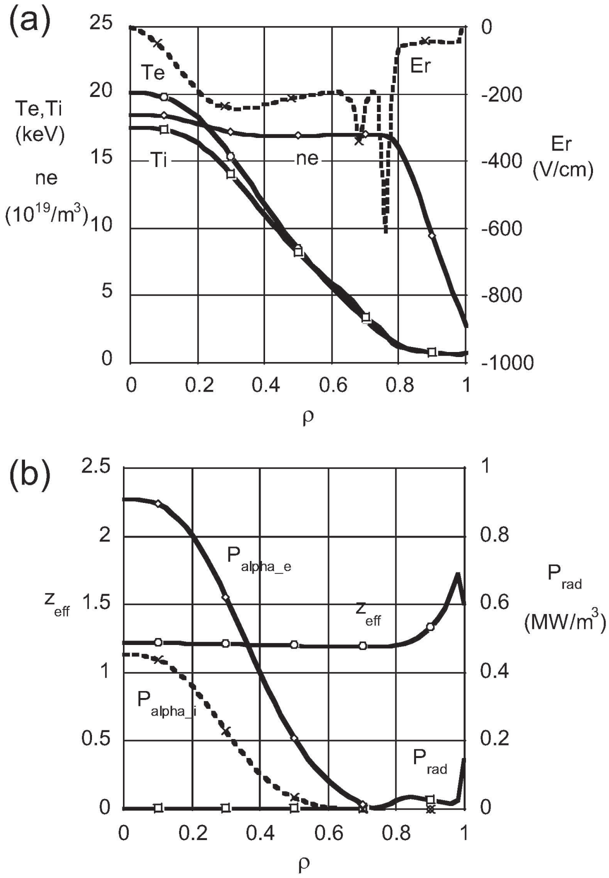

Fig. 3 (a)Temperature, density and radial electric field profiles and (b) power density profiles of ignited LHR-S plasma at $t = 100$ s in Fig. 2.

When the impurity percentage becomes larger, we expect the change in the radial electric field profile related to the impurity transport dynamics. Also, the effect of magnetic configurations on the impurity transport will be analyzed using the present TOTAL code in the future.

4. Summary

(1) We developed the impurity simulation code coupled with 1-D transport / 3-D equilibrium TOTAL (Toroidal Transport Analysis Linkage) code, which is applicable to helical and tokamak systems.

(2) Ambipolar electric filed due to both fuel and impurity ions are treated self-consistently. Multi-species of impurity ions are included in the analysis of feedback

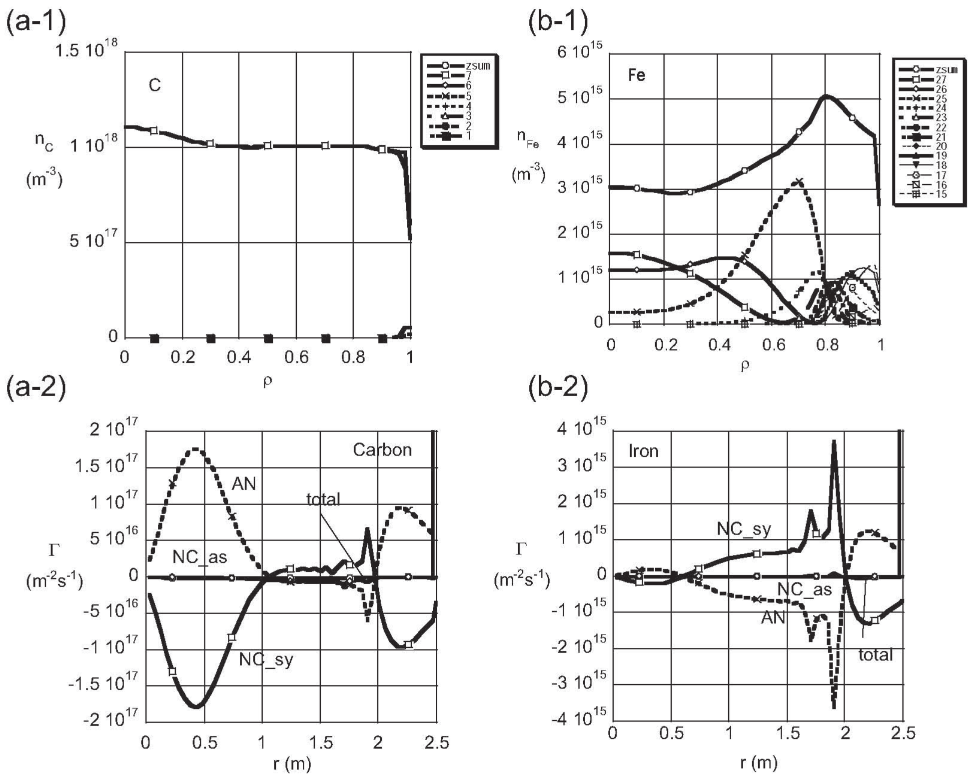

Fig. 4 Carbon (a-1) and Iron (b-1) impurity charge-state density profiles and their particle fluxes (a-2, b-2) as a function of normalized radius. The total flux Γ is the summation of neoclassical symmetric part (NC_sy), asymmetric part (NC_as) and anomalous part (AN).

controlled ignited fusion plasmas.

(3) The present analysis with low impurity contents shows that the neoclassical ripple transport dynamics of impurity ions are small in comparison with axi-symmetric contribution of neoclassical theory. When the anomalous diffusion is introduced, it cancels the neoclassical flux and makes the impurity density profile flat.

(4) Effects of the higher impurity density and the various helical magnetic configurations will be clarified using this TOTAL code in the near future.

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