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Transport analysis of high-Z impurity with MHD effects in tokamak system

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In fusion reactors, extremely high heat load on divertor plates is one of the serious problems, and the use of high-Z material is planned in terms of consistency between "ignited fusion burning" and "plasma facing component (PFC) materials". However, high-Z impurity from these PFC causes large radiation loss even if its content is quite little amount. High-Z impurity transport analysis with MHD effects is carried out using TOTAL code. The critical level of impurity concentration in ITER is found 4.0% for carbon, 0.1% for iron, and 0.008% for tungsten with respect to electron density. The ITB formation for electron density can prevent high-Z impurity accumulation. It is also shown that sawtooth oscillation is beneficial for the reduction of radiation loss from plasma core (~20%), although it might leads to unfavorable fusion power fluctuation of 10%.

Keywords: impurity transport, sawtooth oscillation, internal transport barrier, Tokamak,

1. Introduction

In fusion reactors, the divertor plate and other PFC material get some interactions with hot plasma, by ion backscattering, chemical and physical sputtering processes, and then yield impurities into plasma. Especially heat loads on divertor plates are predicted to be very large, and high-Z materials such as tungsten will be used in such parts due to its high heat conductivity and low erosion rate. However, resulting high-Z impurity tends to accumulate in plasma core due to strong inwardly directed drift velocities caused by neo-classical convection and cause large radiation loss. Besides they displace reacting ions by large number of electrons released by them and cause fuel dilution.

The radial distribution of impurity in tokamak and helical system is calculated by using a 1.5D transport code TOTAL (toroidal transport analysis linkage) [1]. In Section 2, a simulation code used in this paper is described. In Section 3, typical machine parameters and plasma parameters are described. In Section 4, simulation results are presented. First, we clarify the permissible impurity level for ITER plasma. Secondly we make a study of impurity behavior in plasmas with internal transport barrier (ITB). Thirdly, effects of sawtooth oscillation on impurity are investigated. In Section 5, summary and conclusion are presented.

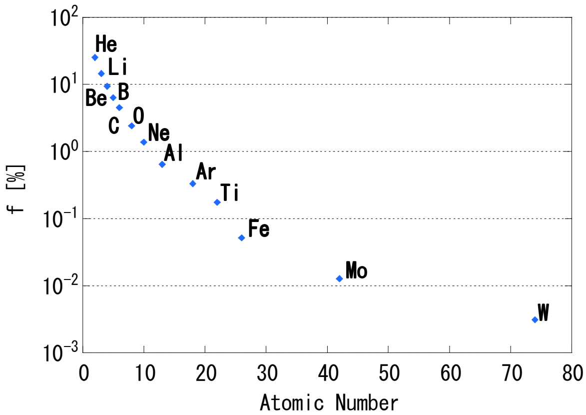

Fig.1 Fractional impurity level which produces radiation power equal to 10% of the total fusion power.

2. Numerical Model

2-1. Transport Model

To investigate transport of fuel and impurity ions in tokamak and helical system, we used 1.5-D (1-D transport / 2-D equilibrium for tokamak), or 2.0-D (1-D transport / 3-D equilibrium for helical) time-dependent simulation model 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

$$\frac{\partial n_e}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho} V'\Gamma_e = S_P \tag{1}$$

$$\sum_i z_i n_i \approx n_e \tag{2}$$

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

$$\frac{3}{2}\frac{\partial n_i T_i}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \rho}\left\{V'\left(q_i + \frac{5}{2}\Gamma_i T_i\right)\right\} = P_{Hi} - P_{ei} - P_{cx} - z_i\Gamma_i E_r \tag{4}$$

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Using the normalized radius ρ and the volume V defines by the equilibrium magnetic surface. The radiation loss P_{rad} is the summation of bremsstrahlung radiation, impurity line radiation and synchrotron radiation powers.

For the anomalous part of the transport coefficients, a Bohm-type model is used in this paper;

$$\chi_e = \chi_i = \alpha_B \frac{T_e}{B_T} q_\Psi^2 / L_{Pe} \quad , \qquad (5)$$

where, T_e, B_t and q_Ψ are the electron temperature, toroidal magnetic field and MHD safety factor, respectively. L_{Pe} is the scale length of the pressure gradient normalized by the minor radius.

We examined high-Z impurities with a model for impurities in TOTAL: the multi-species dynamic impurity code IMPDYN was used to model the ionization states and the NCLASS code was used for the full neoclassical transport of each charge state considering arbitrary aspect ratio and collisionality.

2-2. Impurity Model

For the impurity dynamics [2,3], the rate equation and the diffusion equation are solved using IMPDYN code coupled with ADPAK atomic physics package which can calculate cooling rate:

$$\frac{\partial n_k}{\partial t} = -\frac{1}{V'}\frac{\partial}{\partial \rho}(V\Gamma_k) + [\gamma_{k-1} n_{k-1} + \alpha_{k+1} n_{k+1} - (\gamma_k + \alpha_k) n_k] n_e + S \, . \qquad (6)$$

$$\Gamma_k = \Gamma_k^{NCs} + \Gamma_k^{NCa} - D_k(\rho)\frac{\partial n_k}{\partial \rho} + V_k(\rho) n_k \qquad (7)$$

with ionization rate γ_k , recombination rate α_k and particle source term S_k. Here, diffusion constant D_k and simply modeled velocity $V_k=V(a)\cdot(r/a)$ are used for anomalous transport ($V_k>0$ corresponds to outward velocity). The main fuel neutrals are calculated by the AURORA Monte Carlo code.

The neoclassical impurity flux in tokamak is expressed by

$$\Gamma_k^{NCs} = -D_k^{NC}\nabla n_k + D_k^{NC} n_k \Big[\sum_{l \neq k} (g_{nl\to k}\nabla n_l / n_l) + g_{Ti}\nabla T_i / T_i + g_{Te}\nabla T_e / T_e \, . \qquad (8)$$

The neoclassical ripple transport coefficient in helical system is given by the density gradient, temperature gradient and the radial electric field

$$\Gamma_k^{NCa} \propto D_{rip\nabla n}\nabla n / n + D_{rip\nabla T}\nabla T / T - ZE_r / T \qquad (9)$$

Here, we adopted the neoclassical expression of fuel ions to include the impurity ions in addition to the tokamak-like axi-symmetric neoclassical flux.

The radial electric field in the helical system is determined by the neoclassical transport flux including impurity ions as follows,

$$\left(\sum_k z_k \Gamma_k^{NCa}(E_r) - \Gamma_e^{NCa}(E_r)\right) = 0 \qquad (10)$$

Here, the subscript k denotes fuel ions (D & T), helium and impurity ions. The neutral impurity density is given by

$$v_0 \frac{\partial n_k}{\partial \rho} = S_0 n_e n_0 \qquad (11)$$

Here, v_0 is neutral impurity velocity, and S_0 and n_e is ionization coefficient and electron density at plasma boundary.

In the simulation, the impurity source was defined as the impurity neutral flux on the plasma boundary. When steady state conditions have been established, continuous neutral impurity influx was introduced, and after a transient phase the system settles into a new radiation-enhanced steady state.

3. Model of Tokamak and Helical Plasmas

We considered three reacting or burning plasmas; JET, ITER and helical reactor HR-1.

Table.1 Typical machine and plasma parameters.

	ITER	JET	HR-1
R [m]	6.2	2.9	13
a [m]	2	0.95	2.54
κ	1.7	1.6	-
δ	0.3	0.2	-
B [T]	5.35	3.45	4.6
IP [MA]	9.5	4	-

4. Simulation Results

4-1. Permissible Impurity Level

We clarify the critical impurity content for tokamak plasma. As a result, in ITER, critical concentrations of impurity is 4.0% for carbon, 0.1% for iron, and 0.008% for tungsten impurity with respect to electron density to maintain Q>10.

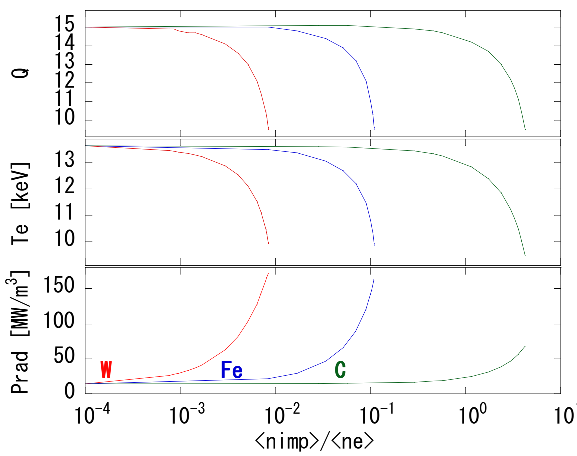

Fig.2 Change of plasma parameters versus impurities concentration.

Regardless of same decrease of Q value for each impurity, they have different radiation power individually. In the case of High-Z impurity (W), the main effect is large radiation loss. On the other hand, it is considered that Low-Z impurity (C) dominates other influence on plasma, such as fuel dilution, rather than radiation itself.

4-2. Effects of Internal Transport Barrier

To control impurity influx, the modification of edge plasma density profile might be beneficial. According to the neoclassical theory, a finite gradient of temperature (i.e. negative $\nabla T/T$) might contribute to the impurity shielding effect. But finite density gradient leads to impurity pinching effect. Figure 3 shows the effects of edge electron density profile in the case of ITB foot-point at ρ=0.8. When the edge density profile becomes rather flat due to strong gradient at temperature ITB, the impurity line radiation can be reduced as shown in the figure.

This result indicates that ITB formation, such as by pellet injection, can prevent high-Z impurities from accumulating inside the ITB.

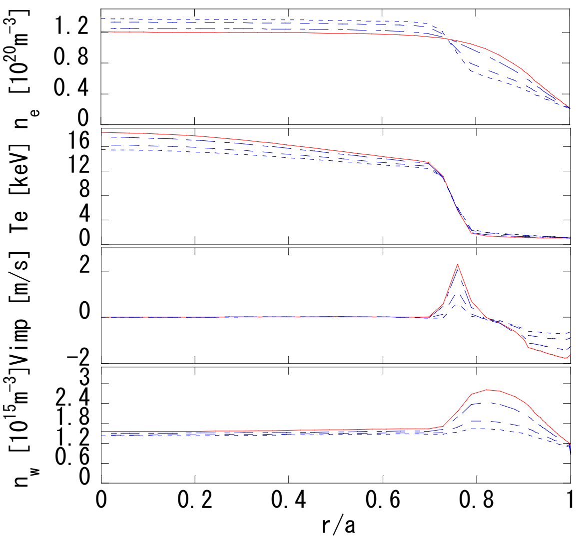

Fig.3 Effect of edge density profile on impurity transport in ITER ITB plasma.

4-3. Effects of Sawtooth Oscillation

Sawtooth oscillations are periodic and MHD-initiated mixing events that occur in a tokamak plasma in the near axis region where the safety factor q is less than or equal to unity. It is known to affect the transport of main plasma and impurity by flattening radial profile of densities and temperatures periodically in the core plasma. Thus, if inward anomalous convection is present, small sawtooth may be considered as beneficial in preventing the accumulation of impurities in the core region. In this paper, we simulate the argon seeding experiments in JET[4,5] and

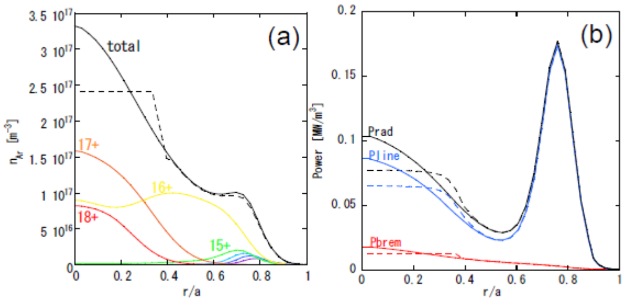

Fig.4 Results of sawtooth oscillation effect on impurity in JET plasma. Figure (a) and (b) shows total impurity density profile, and total radiation profile in the case of argon respectively before (solid line) and after (dashed line) sawtooth crash.

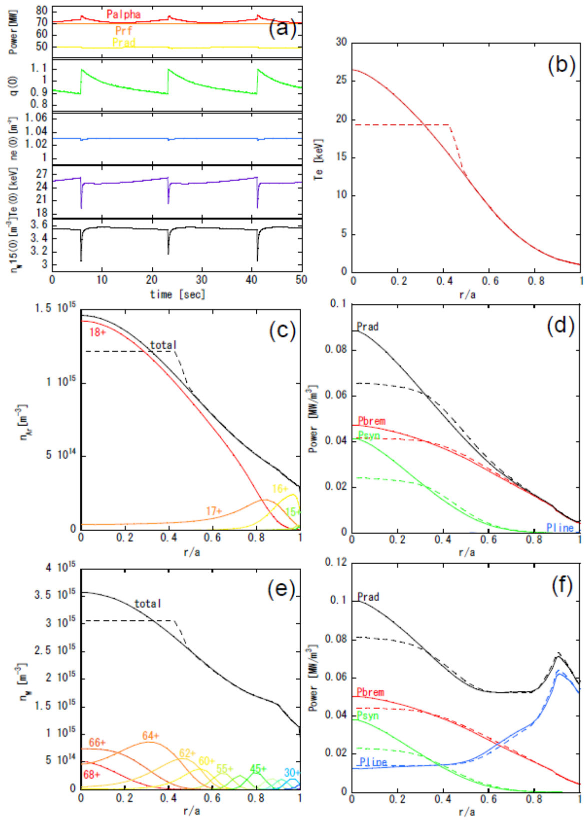

Fig.5 Results of sawtooth oscillation effect on impurity in ITER plasma. Figure (a) and (b) shows time evolution of main plasma parameters and electron temperature, respectively. Figure (c) and (d) shows total impurity density profile and total radiation profile in the case of argon, respectively, before (solid line) and after (dashed line) sawtooth crash. Figure (e) and (f) are the same for tungsten.

also predict the impurity (Ar/W) behavior in ITER discharge with sawtooth in the case of existing relatively large inward drift velocity for impurity.

Simplified sawtooth model is included in the TOTAL code which evolves the plasma profiles between crashes. In the model, the profile is made to be flat inside the inversion radius at the crash, based on the Kadomtsev's full magnetic reconnection model.

As a result, in JET experiments, sawtooth oscillation is found to be effective for controlling impurity [4,5]. Figure 4 shows that sawtooth oscillation in JET can prevent impurity from accumulating into plasma core and can reduce corresponding impurity line radiation about 25% and total radiation loss about 26% from plasma core. The results roughly agree with experimental data.

On the other hand, in ITER, as shown in Fig.5, since argon impurity is almost fully ionized, corresponding line radiation is nearly zero along whole radius except plasma boundary. Similarly, the case of tungsten impurity, existence of highly charged ion in core region makes profile of line radiation hollow. In both cases, sawtooth oscillations reduce bremsstrahlung radiation and synchrotron radiation from plasma core, and about 20% reduction in radiation loss is realized, although it is not affect line radiation profile. It is shown that sawtooth activities can effectively reduce radiation loss from plasma core, which is caused by the temperate and density drop due to internal disruption and might fluctuate about 10% of fusion power. Moreover, the sawtooth event might initiate a seed island for neoclassical tearing mode (NTM). Therefore, the sawtooth avoidance is important for ITER operations.

5. Summary and Conclusion

We investigated transport of high-Z impurity with MHD effects and show the following results:

(1) In ITER, the critical level of impurity concentration is, 4.0% for carbon, 0.1% for iron, and 0.008% for tungsten with respect to electron density.

(2) ITB formation for electron density, such as pellet injection, can prevent high-Z impurity from accumulating inside the ITB region.

(3) Sawtooth oscillation is beneficial for reduction of radiation loss from plasma core (~20%), although it leads to unfavorable fusion power fluctuation of 10%. Moreover, to avoid its harmful effects on NTM excitation and so on, the control of sawtooth oscillation is necessary in spite of impurity exhaust.

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