Simulation study of density dynamics effect on the ELM behavior with TOPICS-IB

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Abstract. Density dynamics effect on the edge-localized-mode (ELM) behavior has been studied by using an integrated simulation code TOPICS-IB based on a 1.5 dimensional transport code with a stability code of peeling-ballooning modes and a transport model of scrape-off-layer (SOL) and divertor plasmas. Neutral models of core and SOL-divertor regions have been integrated with the TOPICS-IB. The TOPICS-IB successfully simulates the behavior of the whole plasma with density dynamics. It is confirmed by varying the density and the temperature instead of artificially enhancing the collisionality in the previous study that the experimentally observed collisionality dependence of the ELM energy loss is caused by the bootstrap current and the SOL transport. Additionally, ion convective and charge-exchange losses are found to enhance the collisionality dependence by the equipartition effect. On the other hand, the ELM particle loss is found to be almost independent of the collisionality, as shown in experiments, due to the density profile before the ELM and the increase of the SOL density during the ELM in addition to the bootstrap current effect.

1. Introduction

Edge localized modes (ELMs) induce sometimes very large heat load to divertor plates and cause the reduction of plate lifetime. Analyses from multi-machine experiments showed that the ELM energy loss increases with decreasing the collisionality [1-3]. Experimental analyses also suggested that the collisionality dependence of the ELM energy loss is mainly caused by the collapse of the electron temperature profile during an ELM crash (electron conductive energy loss) and the collapse of ion temperature and density profiles (ion conductive and convective energy losses) has smaller effect [1-3]. Contrary to the ELM energy loss, the ELM particle loss is almost independent of the collisionality in experiments [1,3]. Although effects of the bootstrap current and the scrape-off-layer (SOL) transport on the ELM energy loss have been discussed [1,2], the physical understanding and quantitative evaluation are not fully accomplished so far.

The integrated simulation code is one of effective methods to study the ELM mechanism [4-9]. For example, an integrated code COCONUT, which integrates 1.5 dimensional (1.5D) core transport code JETTO and 2D divertor code EDGE2D, has been developed and is being used for the study of ELM dynamics [8]. On the other hand, we have developed an integrated code TOPICS-IB [9] with a dynamic five-point model for SOL-divertor plasmas [10] and a stability code for peeling-ballooning modes, MARG2D [11]. The TOPICS-IB is based on a 1.5D core transport code TOPICS extended to the integrated simulation for burning plasmas. The TOPICS-IB successfully simulated a series of transient behaviors of an H-mode plasma; the pedestal growth, an ELM crash and the recovery of the pedestal. At the ELM crash, the increase of SOL temperature mitigates the radial edge gradient and
lowers the ELM energy loss. The collisionality dependence of the ELM energy loss was found to be caused by both the edge bootstrap current and the SOL parallel transport. The collisionality dependence caused by the parallel transport was also pointed out by the analytical model [12]. The steep pressure gradient inside the pedestal top broadens the region of the ELM enhanced transport through the broadening of eigenfunctions and enhances the ELM energy loss [13]. Figure 1 shows TOPICS-IB results of (a) the ELM energy loss, \( \Delta W_{ELM} \), normalized by pedestal energy, \( W_{ped} \), as a function of the normalized collisionality \( \nu^* \) for two cases A and B with different pressure gradient inside the pedestal top at the normalized minor radius \( \rho = 0.925 \) at the ELM onset in figure 1(b). In figure 1(a), the TOPICS-IB reproduced the magnitude of the ELM energy loss and its collisionality dependence in the data of multi-machine and JT-60U experiments [1,14]. In this simulation, however, the density profile is fixed for simplicity. The density collapse enhances the values of \( \Delta W_{ELM} / W_{ped} \) by about 50% through the convective energy loss under the assumption of the similar collapse to the temperature one.

In this paper, we study the effect of the density dynamics on the ELM behavior and the resultant particle and energy losses. The dynamics of the pedestal density strongly connects with the neutral recycling. We integrate neutral models in both the TOPICS and the five-point model. The collisionality dependence of the ELM particle and energy losses is investigated by varying the density and the temperature instead of artificially enhancing the collisionality in the previous study. In the next section, we explain the TOPICS-IB and the integration with neutral models. An integrated simulation result of the whole plasma with the density dynamics is shown in section 3. The pedestal density and temperature are varied by the gas puffing in section 4. The collisionality dependence of ELM particle and energy losses is clarified in sections 5 and 6.

![Figure 1](image1.png)

**Figure 1.** (a) \( \Delta W_{ELM} / W_{ped} \) as a function of \( \nu^* \) for two cases A and B with pressure profiles in (b) where shaded regions denote experimental data [1,14]. (b) Pressure profiles at the ELM onset with different pressure gradients inside pedestal top at \( \rho = 0.925 \).

2. **Integrated code TOPICS-IB for the ELM dynamics**

The ELM dynamics is investigated by the TOPICS-IB, in which the TOPICS is coupled with the ELM model [4] and the SOL-divertor model [10]. Details of the TOPICS-IB are shown in [9]. Some essential features, neutral models and those integration are explained as follows.

2.1. **TOPICS**

TOPICS self-consistently solves the 1D transport and current diffusion equations and the Grad-Shafranov equation of the MHD equilibrium on the 2D plane. The transport equations are the continuity equation for the deuterium ion density, \( n_i \), the power balance equations for the electron temperature, \( T_e \), and the ion temperature, \( T_i \), on the coordinate of the normalized minor radius, \( \rho \),
defined by the square root of the toroidal flux. In this paper, particle and thermal diffusivities are assumed as \( D = D_{\text{neo},i} + D_{\text{ano}} \) and \( \chi_{\text{el}} = \chi_{\text{neo},i} + \chi_{\text{ano},e,i} \), where \( D_{\text{neo},i} \) and \( \chi_{\text{neo},i} \) denote neoclassical ion diffusivities. The anomalous diffusivities \( D_{\text{ano}} \) and \( \chi_{\text{ano},i} \) are simply given as an empirical formula based on JT-60U experiments, \( D_{\text{ano}} = \chi_{\text{ano},e} = 0.18 \left( 1+2p^3 \right) \left( 1+P_{\text{NB}} \right) \text{ m}^2/\text{s} \) and \( \chi_{\text{ano},i} = 2 \chi_{\text{ano},e} \), where \( P_{\text{NB}} \) is the neutral beam power in the unit of MW. In order to produce the H-mode pedestal structure, the transport near the edge is reduced to the neoclassical level (\( D_{\text{ano}} = \chi_{\text{ano},e,i} = 0 \)). The region of the reduced transport is prescribed for simplicity so that the pedestal width, \( \Delta_{\text{ped}} \), is fixed constant.

Neutrals are treated by the 2D Monte-Carlo method, in which the ionization due to electron and ion impacts, and the charge-exchange (CX) are taken into account. The neutrals are assumed to establish its steady-state on each step of the time-evolution of plasmas for simplicity. This assumption is based on that the transit time of neutrals is much shorter than the typical ELM duration of a few 100 \( \mu \text{s} \). For example, the transit time of neutrals with the energy of 3 eV across a length of 0.2 m is 17 \( \mu \text{s} \). The particle flux of neutrals across the separatrix derived from the particle balance model in subsection 2.4 is used as an input for this Monte-Carlo code.

2.2. ELM model
The ELM model [4] has been developed by coupling the TOPICS with a linear MHD stability code MARG2D [11]. In the present simulation, stabilities of \( n=1-50 \) modes are examined by the MARG2D at given time-intervals along the pedestal growth, where \( n \) is the toroidal mode number. When some modes become unstable, an ELM is assumed to occur. The ELM enhanced diffusivities, \( D_{\text{ELM}} \) and \( \chi_{\text{ELM}} \), are added on the basis of radial profiles of eigenfunctions of unstable modes, where \( D_{\text{ELM}} = \chi_{\text{ELM}} = \chi_{\text{ELM}}^{\text{max}} \times \left( \Sigma_n \xi_{n,a}^2 \right)/N \), where \( \chi_{\text{ELM}}^{\text{max}} \) is the maximum value, \( \xi_{n,a} \) denote the radial displacement of the plasma by the unstable mode with specific \( n \), and \( N \) is the total number of the unstable modes with various \( n \). The profile of the radial displacement \( \xi_{n,a} \) is assumed to be the sum of poloidal mode components of the eigenfunction, \( \eta_{p,n,m} \), i.e., \( \xi_{n,a} \propto \Sigma_m \eta_{p,n,m} \), where \( \xi_{n,a} \) is normalized by its maximum value. The ELM enhanced transport is maintained for a time interval \( \tau_{\text{ELM}} \) given as a parameter.

2.3. SOL-divertor model
The five-point model [10] for SOL-divertor plasmas is based on the integral of time dependent fluid equations, i.e., particle, momentum, electron and ion temperatures, generalized Ohm’s law and current equations. The model geometry is an open magnetic flux-tube nearest to the separatrix. The flux tube is divided into four regions: the SOL region divided into two regions at the stagnation point where the parallel particle flux is zero and two divertor regions on either side of the SOL region. The integral fluid equations in each region are reduced to a set of nonlinear equations with physical variables at five positions (stagnation point, upstream throats of divertor regions and sheath entrances). Exponential radial profiles are assumed as \( f(\rho) = f(0) \exp(-\rho a/\lambda_{\rho}) \), where \( f \) denotes each of \( n, T_e, T_i \) and \( a \) is the minor radius. Radial scale lengths, \( \lambda_{\text{re}}, \lambda_{\text{ri}}, \lambda_{\text{rj}} \), are solved in the model. A kinetic-effect model (heat flux limit) based on results from the particle code is introduced. The five-point model can deal with the in-out/up-down asymmetry of divertor plasmas, but the symmetry is assumed in this paper for simplicity. Radial electron particle flux across the separatrix, \( \Gamma_{\text{re}} \), and radial heat fluxes of electrons and ions across the separatrix, \( Q_{\text{e},n} \) and \( Q_{\text{i},n} \), obtained in the TOPICS are used as inputs for the five-point model. Heat and particle diffusivities in the five-point model, \( D_{\text{el}}, \chi_{\text{el}} \), and \( \chi_{\text{el,i}} \), are set equal to those values at the separatrix in the TOPICS. The five-point model calculates the SOL electron density at the separatrix, \( n_{\text{e,SOL}} \), and temperatures, \( T_{\text{e,SOL}} \) and \( T_{\text{i,SOL}} \), which are used as boundary conditions in the TOPICS. During the ELM crash, the radial scale lengths vary along the time evolution and become long according to the ELM enhanced diffusivity at the separatrix. The collisionality dependence in the five-point model appears through the parallel heat conduction and the equipartition energy flow between electrons and ions.
The particle source density due to recycling neutrals in the divertor region, \( S_n \), is given by:
\[
S_n = \eta f_{\text{dr}}/L_d \]
where \( f_{\text{dr}} \) and \( L_d \) denote a particle flux to the divertor plate and a length of the divertor region along the magnetic field line, respectively. The divertor recycling coefficient \( \eta \), which was assumed to be constant in [10], is modeled by:
\[
\eta = (1-f_{\text{dpump}}/f_{\text{dr}})(1-\exp(-\theta \lambda_0/\lambda_\text{iz}))
\]
where \( \theta \) is the pitch of the magnetic field, \( \lambda_0 = \nu_e/(n_{\text{div}}<\sigma v>_n) \) is the ionization mean-free-path of neutrals with the velocity \( \nu_e = (T_e/m)^{1/2} \). The fraction \( f_{\text{dpump}} \) is pumped out from the divertor and the fraction \( f_{\text{dr}} \) radially escapes the divertor region and goes back to the core region. The ionization rate coefficient \( <\sigma v>_n \) is a strong function of the divertor electron temperature, \( T_{\text{div}} \). This model is similar to that used in [15], which is validated by the 2D divertor transport code B2-EIRENE. In the present model, the particle source in the SOL regions is not taken into account.

2.4. Integration of neutral models
We consider the particle balance in core and SOL-divertor regions and integrate neutral models in the TOPICS and the five-point model. Figure 2 illustrates a simple model of the particle balance. Plasma particle flow across the separatrix, \( \Phi_r \), goes to the divertor plates and the first wall. The plasma flow to the divertor plates, \( \Phi_d \), is calculated by:
\[
\Phi_d = 4\pi R \theta_0^L \Gamma_d(r) dr
\]
where \( R \) and \( L \) denote the major radius and a distance between the separatrix and the first wall, respectively. The radial profile of \( \Gamma_d \) is defined as:
\[
\Gamma_d(r) = n_{\text{div}} \exp(-r/\lambda_\text{iz})(T_{\text{div}} \exp(-r/\lambda_e) + 3T_{\text{div}} \exp(-r/\lambda_t))/m^{1/2}
\]
The plasma flow to the first wall, \( \Phi_w \), is calculated by:
\[
\Phi_w = (D_L n_{\text{SOL}}/\lambda_e) \exp(-r/\lambda_e) S_{\text{sep}}
\]
where \( S_{\text{sep}} \) is the area of the separatrix surface. Integration of neutral models

The ELM activity is simulated for JT-60U like parameters: \( R = 3.4 \) m, \( a = 0.9 \) m, \( \kappa = 1.5, \delta = 0.26, I_p = 1.5 \) MA, \( B_i = 3.5 \) T, \( q_{\text{as}} = 4.3-4.6 \) and \( \beta_n \sim 0.7-1.1 \). The ELM parameters are chosen as \( \tau_{\text{ELM}} = 200 \) ms, \( X_{\text{ELM}} \) max = 100 m\(^2\)s\(^{-1}\) and \( A_{\text{ped}} = 0.05 \) on \( \rho \). The values of \( \tau_{\text{ELM}} \) and \( A_{\text{ped}} \) are typical values in JT-60U and other experiments [1,14]. On the other hand, the value of \( X_{\text{ELM}} \) max is chosen to obtain ELM energy and particle losses comparable with JT-60U experiments [14]. As shown in [9,13], these parameters vary the ELM energy loss but the collisionality dependence does not change under the assumption of constant parameters. The pumping and escaping fractions of neutrals in SOL-divertor regions are chosen as \( f_{\text{dpump}} = 0.01, f_{\text{wpump}} = 0 \) and \( f_{\text{dr}} = 0.02 \) in the present study. The distance between the separatrix and the first wall \( L_r = 0.4 \) m and the constant neutral energy \( T_n = 3 \) eV are assumed.

Figure 3 shows the time evolution of profiles of the electron density and temperature (a)(b) before, (c)(d) during and (e)(f) after an ELM crash. The pedestal top and foot are located at \( \rho \sim 0.925 \) and 0.975, respectively (thus \( A_{\text{ped}} = 0.05 \)). The ion temperature at the pedestal top, \( T_{\text{ped}} \sim 2 \) keV, is higher than the electron one \( T_{\text{ped}} \sim 1.3 \) keV at the ELM onset. Figure 4 shows the time evolution of (a) the volume averaged electron density, \( n_e \), (b) the electron part of the stored energy, \( W_e \), the ion part, \( W_i \), the total stored energy, \( W_t \), (c) \( I_{\text{ped}} \), (d) \( Q_t \), (e) \( n_{\text{SOL}} \), the divertor plasma density, \( n_{\text{div}} \), (c) \( T_{\text{SOL}} \) and the divertor plasma temperature, \( T_{\text{div}} \). The simulation starts at nearly stationary state and the reduction of
diffusivities for the pedestal begins at $t = 0.03$ s. Along the pedestal growth, the density and temperature increase in the pedestal region in figures 3(a) and (b) and the averaged density and the stored energies increase in figures 4(a) and (b). The reduction of diffusivities transiently decreases the radial fluxes and the SOL-divertor plasma densities and temperatures in figures 4(c)(d)(e) and (f). The ion SOL temperature is higher than the electron one, while the divertor plasma temperatures is lower than the SOL ones due to the high recycling divertor plasma.

![Figure 3](image1.png)

Figure 3. Time evolution of $n_e$ and $T_e$ profiles (a)(b) before, (c)(d) during and (e)(f) after an ELM crash. In (a)(b), lines denote 50 ms interval from $t = 0$ s to 0.2 s in figure 4. In (c)(d), 40 μs interval from $t = 0.2$ s to 0.2002 s. In (e)(f), 0.2 ms interval from $t = 0.2$ s to 0.201 s.

In the progress of the pedestal growth, the high-$n$ modes ($n = 10,11$) become unstable and an ELM occurs at $t = t_{ELM} = 0.2$ s. The profile of the ELM enhanced diffusivity is shown in figure 7(c) (case B). The collapse of the density and temperature profiles occurs in the pedestal region in figure 3(c) and (d). The drop of $n_e$ at the pedestal top is about 30 % of $n_{ped}$ and $T_e$ drop is about 40 % of $T_{ped}$, which are comparable with those in experiments [2-4]. Pedestal particle and energy flow into the SOL and the SOL-divertor densities and temperatures rapidly increase as shown in figures 5(a)(b)(c) and (d). The increase of the SOL density and temperature mitigates radial edge gradients and lowers the ELM particle and energy losses. Figures 5(e) and (f) show the time evolution of (a) $\langle n_e \rangle$, (b) $W_{ei}$, $W_{ed}$, $W_e$, (c) $Q_{ri}$, (d) $Q_{ei}$, (e) $n_{SOL}$, $n_{div}$, (f) $T_{SOL}$, $T_{ediv}$, $T_{div}$. Profiles are shown in figure 3. The ELM particle loss occurs only in the ELM duration of $t_{ELM} = 200$ μs. The resultant ELM particle loss is less than 10 % of the pedestal particle
and is comparable to those obtained in experiments [1,3,14]. On the other hand, the ELM energy loss continues about 1 ms after the ELM duration. The resultant ELM energy loss is less than 10 % of the pedestal energy and is comparable to those in JT-60U [14]. Because of the flat temperature (pressure) gradient inside the pedestal top at the ELM onset in figure 3(b), like the case A in figure 1, the ELM energy loss in this simulation is small compared with multi-machine experiments [1].

4. Pedestal density and temperature variations by gas puffing
In order to study the collisionality dependence of ELM particle and energy losses, the density and the temperature are varied by the gas puffing. Figure 6 shows profiles of (a) the electron density, (b) the electron temperature and (c) the total pressure, $P$, at the ELM onset for various amounts of gas-puffing flow (A) $\Phi_{puf} = 0$, (B) $0.3 \times 10^{22}$, (C) $0.9 \times 10^{22}$ and (D) $2 \times 10^{22}$ s$^{-1}$. The case B is the same as shown in figures 3-5. The gas puffing increases the pedestal density and decreases the pedestal temperature. Thus, the normalized electron collisionality of the pedestal plasma, \( \nu_{\text{ped}} = \frac{\lambda_{ee}}{\rho} \), where \( \lambda_{ee} \) is the electron mean free path, increases from 0.11 to 2.1 in figure 6. The gas puffing also reduces the density pedestal width by increasing the particle source near the separatrix in figure 6(a), while pedestal widths of the temperature and the total pressure are almost constant in figures 6(b) and (c). At the ELM onset, the pedestal pressure decreases with increasing the density except for the case A.

Figure 7 shows profiles of (a) the bootstrap current, $j_{BS}$, (b) the magnetic shear, $s$, at the ELM onset and (c) $D_{\text{ELM}}(\chi_{\text{ELM}})$ during the ELM. For higher collisionality, the bootstrap current decreases and the magnetic shear increases except for the case A in figures 7(a) and (b). The increase of the magnetic
shear reduces the width of eigenfunctions of unstable modes. Unstable mode numbers vary from medium to high values; (A) \( n = 10,11,14 \), (B) 10,11, (C) 26-38 and (D) 48-50. Only in the case D, the infinite ballooning mode is already unstable. Even if the transport are assumed to be also enhanced by the infinite ballooning mode, the simulation result in the case D does not change very much because the pressure profile at the onset of the infinite ballooning mode is a little lower than that in figure 6(c) and the width of the unstable region is similar to that of the eigenfunctions in the result of figure 7(c). As a result of higher collisionality, the bootstrap current suppression reduces the area of the ELM enhanced transport in figure 7(c). This behavior is the same as found in the previous study [9], in which the collisionality is artificially enhanced in the bootstrap current model.

Figure 7. Profiles of (a) \( j_{BS} \), (b) \( s \) at the ELM onset and (c) \( D_{ELM}(x_{ELM}) \) during ELM for the same cases as in figure 6.

Figure 8. Time evolution of (a) \( n_{eSOL}, n_{ediv} \), (b) \( T_{eSOL}, T_{ediv}, T_{ISOL} \) and \( T_{idiv} \) during and after an ELM crash for case A in figure 6. (c)(d) Time evolution for case D.

The results in the case A shown above are different from the other cases B-D. This difference results from the recycling condition of divertor plasmas. Figure 8 shows the time evolution of densities and temperatures of SOL-divertor plasmas during and after the ELM crash in the cases A and D. The time evolution in the case B is already shown in figures 5(c) and (d). Without the gas-puffing in the case A, the divertor plasmas are under the low recycling condition with low density and high temperature before the ELM. The divertor plasma density is lower than the SOL density and the electron temperature is almost constant along the field line, \( T_{eSOL} \sim T_{ediv} \). The gas puffing changes the condition before the ELM from the low recycling in the case A to the high recycling in the cases B-D where the divertor density is higher than the SOL density and the divertor temperature is lower than the SOL temperature. The ELM transiently changes the above conditions of the SOL-divertor plasmas. For lower amount of the gas puffing and hence lower collisionality, the ion SOL temperature is higher than the electron one due to the ineffectiveness of equipartition energy flow from ions to electrons. The low recycling condition before the ELM in the case A results in the different ELM behavior from
the other cases, as shown in figures 6, 7, 9 and 11-12. Because the low recycling divertor is not desirable from the viewpoint of the damage of divertor plates, the divertor seems to be under the high recycling condition in the majority of experiments. Thus, hereafter, the results in the cases B-D will be mainly discussed.

5. Collisionality dependence of ELM particle loss
The collisionality dependence of the ELM particle loss is next investigated by using the results in the previous section. Figure 9(a) shows the collisionality dependence of the ELM particle loss, $\Delta N_{\text{ELM}}$, where the outflow loss across the separatrix, $\Delta N_I$, and the particle source, $\Delta N_s$, are also shown. Here, the ELM particle loss $\Delta N_{\text{ELM}}$ is defined by the magnitude of $\delta N$ at which $\delta N$ becomes the lowest value, ex. $t-t_{\text{ELM}} = 0.2$ ms in figure 5(e). The ELM particle loss is determined by the balance between the outflow loss and the source as shown in figure 9(a). Components of the particle source from the divertor, $\Delta N_{\text{div}}$, from the first wall, $\Delta N_{\text{wall}}$, and from the gas puffing, $\Delta N_{\text{spuf}}$ are shown in figure 9(b). The major part of neutrals, which becomes the source, comes from the divertor, especially for the high collisionality. Except for the case A, the outflow loss increases a little with the collisionality while the source increases in figure 9(a). As a result, the ELM particle loss decreases only a little with the collisionality. Thus, the ELM particle loss is almost independent of the collisionality.

Figure 9. Collisionality dependence of (a) $\Delta N_{\text{ELM}}$, $\Delta N_I$, $\Delta N_s$, (b) $\Delta N_{\text{div}}$, $\Delta N_{\text{wall}}$, and $\Delta N_{\text{spuf}}$ for the same cases as in figure 6. All values are normalized by $N_{\text{ped}}$.

This collisionality independence is due to the density profile before the ELM and the increase of the SOL density during the ELM in addition to the bootstrap current effect as shown in figure 10(a). As mentioned in the previous section, the density pedestal width becomes narrow due to the particle source near the separatrix for the high collisionality. Additionally, the increase of the SOL density at $\rho = 1$ becomes small for the high collisionality as shown in the comparison between the case B and D in figure 10(a). The increase of the SOL density depends on a ratio of $\Delta N_I$ to the outflow loss without the ELM, $\Delta N_{I0}$. For higher collisionality, the outflow loss becomes small compared with that without the ELM as shown in figure 10(b), which results in the small increase of the SOL density. The SOL-divertor plasmas are less influenced by the ELM particle loss for the high collisionality. Due to the bootstrap current effect on the ELM enhanced transport discussed in the previous section, the collapse
region becomes narrow in $\rho < 0.95$ for the high collisionality in figure 10(a). As a result, from the case B to D, the magnitude of the particle loss becomes about twice. But the pedestal particle $N_{\text{ped}}$ also increases about twice. Thus, the value of $\Delta N_{\text{ELM}}/N_{\text{ped}}$ does not change much.

6. Collisionality dependence of ELM energy loss

The collisionality dependence of the ELM energy loss is examined by using the results in section 4. Figure 11(a) shows the collisionality dependence of the ELM energy loss $\Delta W_{\text{ELM}}$, its electron component, $\Delta W_e$, and ion one, $\Delta W_i$, where a shaded line denote the ELM energy loss obtained by artificially varying the collisionality in models of the bootstrap current and the SOL-divertor plasmas for a plasma with $\nu^* \sim 0.7$. Here, the ELM energy loss $\Delta W_{\text{ELM}}$ is defined by the magnitude of $\delta W_i$ at which $\delta W_i$ becomes the lowest value, ex. $t_{\text{ELM}} - t_{\text{ELM}} = 1$ ms in figure 5(f). When the collisionality increases by one order of magnitude, the electron and ion energy losses become about half except for the case A. As a result, the total energy loss becomes about half. The electron component of the ELM energy loss and its collisionality dependence are mainly determined by the conductive energy outflow loss across the separatrix, $\Delta W_{\text{ecd}}$, as shown in figure 11(b). The electron convective loss, $\Delta W_{\text{ecv}}$, is small and its collisionality dependence is weak compared with the conductive one. The weak dependence of the electron convective loss on the collisionality is due to the ELM particle loss shown in figure 9(a). The behavior of the electron conduction is the same as found in the previous study [9], in which the collisionality is artificially enhanced in the SOL-divertor model as well as the bootstrap current one. Thus, the shaded line in figure 11(a) is explained only by the electron energy loss with the assumption of the constant ion loss. In figure 11(a), however, the reduction of the total energy loss is larger that caused by the bootstrap current and the SOL transport. This large reduction is due to the ion energy loss.

![Figure 11](image1.png)

**Figure 11.** Collisionality dependence of (a) $\Delta W_{\text{ELM}}$, $\Delta W_e$, $\Delta W_i$ (b) $\Delta W_{\text{ecd}}$ and $\Delta W_{\text{ecv}}$ for the same cases as in figure 6, where a shaded line denote $\Delta W_{\text{ELM}}$ obtained by artificially varying collisionality in models of bootstrap current and SOL-divertor plasmas. All values are normalized by $W_{\text{ped}}$.

![Figure 12](image2.png)

**Figure 12.** Collisionality dependence of (a) $\Delta W_{\text{ecd}}$, $\Delta W_{\text{ecv}}$, $\Delta W_{\text{CX+iz}}$, (b) $T_{\text{ped}}/T_e$, $T_{\text{ped}}/T_{\text{ped}}$, and $T_{\text{SOL}}/T_{\text{SOL}}$ at the ELM onset for the same cases as in figure 6. In (a), all values are normalized by $W_{\text{ped}}$. 

Figure 12 (a) shows the collisionality dependence of the ion conductive energy outflow loss, $\Delta W_{\text{icd}}$, the convective loss, $\Delta W_{\text{icv}}$, and the energy loss due to the CX corrected by the energy source due to the ionization, $\Delta W_{\text{CX+iz}}$. In the ion energy loss, the convective loss is larger than the conductive and CX ones. The ion convective and CX losses decrease with increasing the collisionality, while the...
The convective loss does not change much. The collisionality dependence of both the convective and CX losses is caused by the equipartition effect as shown in figure 12(b). For lower collisionality, the pedestal and SOL ion temperatures become higher than the electron ones. If the ion temperature is equal to the electron one, the collisionality dependence of the ion convective and CX losses become weak like the electron convective loss in figure 11(b). As a result, the ion convective and CX losses enhance the collisionality dependence of the ELM energy loss.

7. Conclusion
Density dynamics effect on ELM behavior has been studied by using the TOPICS-IB. Neutral models of core and SOL-divertor regions have been integrated with the TOPICS-IB. The TOPICS-IB successfully simulates the behavior of the whole plasma with density dynamics. The ELM particle loss is found to be almost independent of the collisionality, as shown in experiments, due to the density profile before the ELM and the increase of the SOL density during the ELM in addition to the bootstrap current effect. It is confirmed by varying the density and the temperature instead of artificially enhancing the collisionality in the previous study that the collisionality dependence of the ELM energy loss is caused by the bootstrap current and the SOL transport. Additionally, the ion convective and CX losses are found to enhance the collisionality dependence by the equipartition effect.

In order to validate our models, simulations for various tokamaks and comparisons with experiments and nonlinear simulations are our future works. The model improvement, such as the transport model which determines the pressure gradient inside the pedestal top as well as the pedestal width, and so on, is necessary. We will consider effects of the localization of ELMs at the low-field side midplane and the filamentary structure [16,17], which are not taken into account in the present model as the same in other integrated codes [5-8]. The ELM cycle following the first ELM shown in this paper will be studied in future.

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