EMC3-EIRENE modelling of tungsten behavior under resonant magnetic perturbations on EAST: Effects of tungsten sputtering and impurity screening

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Abstract
The studies on tungsten (W) sputtering and transport characteristics on EAST tokamak under resonant magnetic perturbation (RMP) fields have been performed with the three-dimensional edge transport code EMC3-EIRENE. The estimation of the W sputtering flux has been carried out based on EMC3-EIRENE modeling for RMP and no RMP applications. The W sputtering flux shows a small difference between RMP and no RMP cases due to weak sensitivity of W sputtering yield on deuterium impact energy for low edge plasma density. However, for high edge plasma density, the strong dependence of W sputtering yield on deuterium impact energy comes into play, which results in a remarkable difference in the W sputtering flux between RMP and no RMP cases. Impacts of the W impurity perpendicular transport on W ions transport have been investigated. With low W perpendicular transport coefficient for RMP case, the edge plasma has a better W ions screening effect for high edge plasma density. The increased W perpendicular transport coefficient results in a good W ions screening effect for both high and low edge plasma densities.

Keywords: resonant magnetic perturbation, impurity sputtering, impurity screening

1. Introduction
Edge impurity transport is critical to sustaining long-term and steady-state operation regime in fusion devices [1, 2]. For axisymmetric magnetic configuration in tokamaks, impurity transport along parallel magnetic field lines in the scrape-off layer (SOL) is mainly determined by the force balance acting on the impurities [3–6]. For stellarators and tokamaks with resonant magnetic perturbation (RMP) application, three-dimensional (3D) edge magnetic topology leads to an intricate edge plasma and impurity transport behavior [7–15]. High Z materials such as tungsten (W) are commonly employed as the plasma-facing components in existing and...
next-step fusion facilities due to its small physical sputtering yield and low co-deposited tritium inventory \[16, 17\]. However, W impurity during penetration into the plasma core region can dramatically deteriorate energy confinement and even render discharge termination due to severe bremsstrahlung. Therefore, studies on the effects of RMP fields on W transport are essential to achieve impurity screening and high-performance plasma.

The transport behaviors of the unresolved transition array (UTA) of W in the wavelength range of $\lambda = 48–70$ Å under RMP fields on EAST tokamak have been monitored by the extreme ultraviolet spectrometer \[18, 19\]. Figure 1 displays the time evolution of W UTA emission under RMP application for shot #67578 on EAST. The RMP fields are triggered from $t_{\text{RMP}} = 3$ s indicated by the vertical dashed line in figure 1. It can be seen that RMP application results in a dramatic decrease of 70% in the W UTA emission intensity. Additionally, our previous works have demonstrated that 20% reduction in the CVI emission (emitted by $\text{C}^5+$) can be achieved under RMP application \[20\].

Since the W emission wavelengths (48–70 Å) are unresolvable based on the current spectrometric diagnostics on EAST, it is difficult to make a detailed numerical modeling to reproduce the above-mentioned reduction in W emission under RMP application. Given that RMP-induced variation of edge magnetic topology leads to 3D erosion of divertor targets and edge stochastization \[15\], it can be anticipated that W sputtering and impurity screening effects play important roles in the W density and emission distributions. However, influences of the 3D magnetic topology induced by RMP fields on W sputtering and transport behaviors are not well understood yet for tokamak devices. It is interesting to examine whether there exist certain common physics behind the effects of W sputtering and impurity screening induced by RMP fields.

In this work, changes in the W sputtering and transport behaviors under RMP application on EAST have been investigated with 3D edge transport code EMC3-EIRENE \[21, 22\]. In light of diagnostic difficulties in the measurements of W emission as mentioned above, our attention is focused on understanding of influences of the RMP fields on W sputtering and transport behaviors, rather than on reproducing the experimental results of decrease in the W UTA emission. Estimations of W sputtering flux and spatial amount with and without RMP applications have been conducted by EMC3-EIRENE. Detailed analysis of impacts of edge plasma parameters and impurity perpendicular transport coefficient has been attempted to study the changes in W sputtering and edge transport behaviors induced by RMP fields. It is found that the enhanced tungsten perpendicular transport under RMP application plays a more important role in interpreting the remarkable reduction in W emission for the studied discharge in comparison with the effects of W sputtering flux. In section 2, the plasma and impurity transport models in EMC3-EIRENE code are briefly introduced. Simulations related to the effects of W sputtering and impurity screening are conducted in section 3. Finally, the results are summarized in section 4.

2. The EMC3-EIRENE code

The EMC3-EIRENE code was originally applied for edge plasma and impurity transport modeling on stellarators, and has been extensively used on tokamaks with and without RMP fields in recent years \[23\]. A reduced set of Braginskii fluid equations for the particle, momentum and energy transport of ions and electrons is solved by the EMC3 code, which is self-consistently coupled with the kinetic neutral particle transport code EIRENE \[21, 22\]. The fluid equations are solved by the Monte Carlo (MC) method to obtain the steady-state plasma
profiles of the connection length for the equilibrium (a) and perturbed cases (b) and the corresponding perturbation spectrum under RMP fields (c). The Poincaré plots for the equilibrium and perturbed cases are superimposed on the connection length distribution.

Figure 2 shows the 3D schematic diagram of the RMP coil system on EAST [20], which is composed of two coil arrays with the up-down symmetry structures. There are eight coils (each coil has four turns) uniformly distributed along the toroidal direction for each coil array. The maximum coil current is designed to be 10 kA (≈2.5 kA × 4 coil turns). The kth coil current in an array is prescribed by the relation $I_k = A \cos(n \varphi_k - \varphi_0)$, where $A$ is the amplitude, $n$ is the toroidal mode number, $\varphi_k$ is the toroidal angle of the kth coil center and $\varphi_0$ is the phase of each array of coils. $\varphi_0$ is always referred to as current phases $\varphi_U$ and $\varphi_L$ for upper and lower coils.

3. Simulation results

3.1. Setup of EMC3-EIRENE simulations

The magnetic field structures for equilibrium and perturbed fields and input parameters for plasma and impurity mainly refer to our previous EMC3-EIRENE modeling of carbon transport in [20]. The same magnetic configurations as that in [20] for shot #67578 (deuterium discharges and toroidal magnetic field of $B_t = 2.48$ T) are used here. The computational grids for equilibrium and perturbed cases are constructed at two timings ($t = 2.5$ and $5.5$ s), respectively. For axisymmetric equilibrium fields, the EFIT code [27] has been commonly applied to construct the computational grids for EMC3-EIRENE modeling on EAST [28–30]. For perturbation fields, the vacuum approach is employed in this work by superimposing the vacuum perturbed field on the EFIT equilibrium field [10–12, 20]. The plasma response effects to the RMP fields are not taken into account in the present work [31]. The computational grid is constructed as a disconnected double null magnetic configuration (biased towards the upper single null). The $360^\circ$ computational grid spans the whole toroidal simulation domain.

A self-consistent treatment of impurity transport has been involved in the EMC3 code [26]. The friction force and the ion thermal force are the dominant forces that determine the impurity transport in the edge plasma [3]. Both the friction force and the ion thermal force are related to edge plasma parameters, and hence the force balance between them can be altered by background plasma conditions. The feedback of impurities on the background plasma is treated by the energy sinks due to excitation and ionization of impurities.

Table 1. Summary of individual $\chi_\perp$ for no RMP cases.

| $n_u$ (m$^{-3}$) | $\chi_\perp$ (m$^2$ s$^{-1}$) |
|-----------------|------------------|
| 0.73            | 4.0              |
| 1.0             | 3.0              |
| 1.25            | 3.0              |
| 1.5             | 2.7              |

The computational grids are aligned with field lines in EMC3, which can offer effective access to fast magnetic field reconstruction during the MC particle tracing based on the reversible field line mapping technique [24, 25]. Transport parallel to magnetic field lines is treated as classical transport, while anomalous diffusion is assumed for perpendicular transport. A self-consistent treatment of impurity transport has been involved in the EMC3 code [26]. The friction force and the ion thermal force are the dominant forces that determine the impurity transport in the edge plasma [3]. Both the friction force and the ion thermal force are related to edge plasma parameters, and hence the force balance between them can be altered by background plasma conditions. The feedback of impurities on the background plasma is treated by the energy sinks due to excitation and ionization of impurities.

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Figure 5. Profiles of midplane plasma temperature at $\psi_N \approx 0.8$ for RMP ($\chi_\perp = 2.0 \text{ m}^2 \text{s}^{-1}$) and no RMP (varied $\chi_\perp$) applications with $n_e = 0.73 \times 10^{19} \text{ m}^{-3}$ (a), $1.0 \times 10^{19} \text{ m}^{-3}$ (b), $1.25 \times 10^{19} \text{ m}^{-3}$ (c) and $1.5 \times 10^{19} \text{ m}^{-3}$ (d).

coil arrays, respectively. Here, the information of RMP application ($n_e = 1$, $A = 8.8 \text{ kAt}$, $\varphi_U = 21^\circ$ and $\varphi_L = 158^\circ$) is used for discharge #67578. Detailed introduction to the RMP coil system on EAST is presented in [32–34].

The 2D distributions of the connection length ($L_c$) for the equilibrium and perturbed cases at the toroidal angle of $\varphi = 0^\circ$ are presented in figures 3(a) and (b), respectively. The $L_c$ (>1000 m) inside the unperturbed separatrix is much larger than that (<200 m) in the SOL region in figure 3(a). The helical lobes are created in figure 3(b) by the splitting of the unperturbed separatrix into multiple invariant manifolds [35]. The Poincaré plots for the equilibrium and perturbed cases are superimposed on the $L_c$ distributions. It can be seen that the smooth flux surfaces exist for the equilibrium case while the RMP fields lead to a stochastic magnetic geometry in the edge region. Additionally, the perturbation spectrum under RMP fields is displayed in figure 3(c), which indicates the ratio of radial perturbed magnetic field ($b^r$) to toroidal equilibrium field ($B^t$). The resonant condition $m = n q$ is signified by the blue dashed line. The red line segments denote the radial range covered by the islands induced by RMP fields.

The upstream density ($n_u$) and input power ($P_{\text{SOL}}$) are treated as the individual boundary conditions for particle transport and energy transport in the simulations. The normalized poloidal magnetic flux $\psi_N$ ($\approx 0.7$) is employed to define the inner radial boundary at the upstream region. Here $\psi_N = (\psi - \psi_{\text{ax}})/(\psi_{\text{sep}} - \psi_{\text{ax}})$ where $\psi_{\text{ax}}$ and $\psi_{\text{sep}}$ are the poloidal magnetic fluxes at the axis and the separatrix, respectively. The absorbed input power ($P_{\text{SOL}} = 2.3 \text{ MW}$) is injected through the inner radial boundary into the simulation domain. For the perturbed cases, the setup of upstream density ($n_e = 0.73 \times 10^{19} \text{ m}^{-3}$ at $\psi_N \approx 0.8$), cross-field particle transport coefficient ($D_\perp = 0.4 \text{ m}^2 \text{s}^{-1}$) and energy transport coefficient ($\chi_\perp = 2.0 \text{ m}^2 \text{s}^{-1}$) of background plasma is consistent with the previous EMC3-EIRENE modeling for shot #67578 [20], which is determined by comparing with the measured data by edge reciprocating probe on EAST. In addition, the parameter studies with different $n_u = 1.0 \times 10^{19}$, $1.25 \times 10^{19}$ and $1.5 \times 10^{19} \text{ m}^{-3}$ are also performed in the simulations.

For the equilibrium cases, there are no experimental data to match for determining $n_u$, $D_\perp$ and $\chi_\perp$ [20]. The line-averaged electron density maintains stable during shot #67578 (figure 2(c) in [20]), so $n_u$ and $D_\perp$ for the equilibrium cases are assumed to be same as the RMP case in the simulations. In the DIII-D experiments, it is found that the application of RMP fields can lead to a reduction of edge plasma temperature at $\psi_N \approx 0.8$ by about 30%–40% compared to the equilibrium case [36]. The same tendencies of the strong decrease in the edge plasma temperature under RMP application have been grasped by EMC3-EIRENE modeling for NSTX [12] and DIII-D [13] as well. Hence, we conduct a parameter study of
3.2. Tungsten sputtering

Ion impinging energy on divertor targets is considered as a decisive parameter for calculating the physical sputtering of wall material [38]. The edge plasma temperature plays an important role in determining the ion impinging energy and resulting physical sputtering yield [3, 39]. Hence, RMP-induced variation of the edge plasma temperature perhaps can affect the W sputtering behavior on EAST. Figure 4 shows 2D distributions of edge plasma temperature for the cases with and without RMP applications at the toroidal angle of $\psi = 0^\circ$. The same $\chi_\perp (= 2.0 \text{ m}^2 \text{s}^{-1})$ is used in EMC3-EIRENE modeling of RMP and no RMP cases. It can be seen that the edge plasma temperature inside the separatrix is much lower for the perturbed case than that for the equilibrium case in figure 4. The similar phenomenon has also been attained by the previous studies on NSTX [12] and DIII-D [13, 36]. In order to study the impacts of edge plasma temperature on W sputtering, a parameter scan of $\chi_\perp$ has been performed for the equilibrium case.

Figure 5 displays midplane plasma temperature at $\psi = 0.8$ for RMP and no RMP applications for different $n_0$. The selection of the radial position ($\psi_N \approx 0.8$) is same as above-mentioned DIII-D analysis. For $\chi_\perp = 2.0 \text{ m}^2 \text{s}^{-1}$, the plasma temperature for RMP case is lower than that for no RMP case, which are reduced by 42%, 33%, 31% and 23% for $n_0 = 0.73 \times 10^{19}, 1.0 \times 10^{19}, 1.25 \times 10^{19}$ and $1.5 \times 10^{19} \text{ m}^{-3}$, respectively. The increase in $\chi_\perp$ leads to a lower plasma temperature for the equilibrium case in figure 5. Since there are no available experimental data for the equilibrium case, it is difficult to judge to what extent the edge plasma temperature can be reduced by RMP fields. In order to restrict the uncertainty in edge plasma temperature for the equilibrium case, we impose a constraint on the variation range of $\chi_\perp$ i.e. the plasma temperatures for the equilibrium cases should approximate to that for the perturbed cases in figure 5. The simulated plasma temperatures indicated by the blue balls in figure 5 satisfy the above condition for different $n_0$. The corresponding $\chi_\perp$ for the equilibrium cases are summarized in table 1. To facilitate the following discussion, the different values of $\chi_\perp$ in table 1 are referred to as individual $\chi_\perp$ while same $\chi_\perp$ denotes that $\chi_\perp = 2.0 \text{ m}^2 \text{s}^{-1}$ is used for different $n_0$.

The W physical sputtering yield ($Y$) is determined by $D^+$ impact energy and incident angle according to empirical formula in [38]:

$$
Y(E_0, \alpha_0) = Y(E_0, \alpha_0 = 0^\circ) \cdot \left(\cos \alpha\right)^{-f} \cdot \exp\left(f \cdot \left[1 - \frac{1}{\cos \alpha}\right] \cdot \cos \alpha_{\text{opt}}\right) \tag{1}
$$

where $E_0$ is impact energy and $\alpha_0$ is incident angle. The values $f$ and $\alpha_{\text{opt}}$ are fitting parameters and the detailed expressions can be found in [38]. The $D^+$ impact energies $E_0$ are calculated by the relation $E_0 = 2T_i + 3T_e$ based on the edge plasma temperature simulated by EMC3-EIRENE [3, 39]. The $D^+$ incident angle calculated by particle-in-cell method is around $60^\circ$ for the oblique magnetic field lines in fusion devices [40–42]. As a result, the W sputtering flux can
between RMP and no RMP cases, the W sputtering flux ratio is used as shown in figure 6, which presents the ratio of W sputtering flux for the perturbed case to that for the equilibrium case. It can be seen that the RMP application results in a reduced W sputtering flux compared to the equilibrium case. For both same and individual \( \chi_{\perp} \) it has been examined that the plasma temperatures near divertor targets are larger for the equilibrium cases than the perturbed cases. Hence, smaller \( D^+ \) impact energies and W physical sputtering yields are obtained for the perturbed cases, which leads to a lower resultant W sputtering flux compared to the equilibrium case for different \( n_u \) in figure 6.

The increase in \( n_u \) leads to a strong decrease in W sputtering flux ratio as shown in figure 6. This can be interpreted by the dependence of W physical sputtering yield on \( D^+ \) impact energy presented in figure 7. For \( n_u = 0.73 \times 10^{19} \text{ m}^{-3} \), the calculated physical sputtering yields are about \( 3\sim4.0 \times 10^{-3} \) for RMP and no RMP cases according to EMC3-EIRENE modeling. However, for higher \( n_u (>1.0 \times 10^{19} \text{ m}^{-3}) \), the physical sputtering yields are below \( 1.0 \times 10^{-3} \) for RMP and no RMP cases. The W physical sputtering yield \(<1.0 \times 10^{-3}\) becomes more sensitive to the \( D^+ \) impact energy as shown in figure 7. The small change in the edge plasma temperature (i.e. \( D^+ \) impact energy) can lead to a large difference in the W physical sputtering yield between RMP and no RMP cases. Therefore, a reduced W sputtering flux ratio is attained for high \( n_u \) in figure 6. While it can be seen that the decrease in W sputtering flux ratio is not monotonic. The increase in \( n_u \) leads to an increased incident flux of deuterium ions \( (\Gamma_{D^+}) \) while a reduced W physical sputtering yield. Hence, the variation of the resulting W sputtering flux \( (\Gamma_{D^+} \times Y) \) ratio is non-monotonic.

In addition, the plasma temperatures for individual \( \chi_{\perp} \) are lower than that for same \( \chi_{\perp} \) as shown in figure 5, which results in a lower W sputtering flux while a higher W sputtering flux ratio for individual \( \chi_{\perp} \) in figure 6. The shadow area in figure 6 indicates the variation of W sputtering flux ratio induced by uncertainty in edge plasma temperature for the equilibrium cases. Further, for high \( n_u \), the difference in the W sputtering flux ratio between same and individual \( \chi_{\perp} \) is

**Figure 8.** Profiles of W ions amounts for RMP and no RMP cases (a) and W ions amount ratio between RMP and no RMP cases (b) with \( n_u = 0.73 \times 10^{19}, 1.0 \times 10^{19}, 1.25 \times 10^{19} \) and \( 1.5 \times 10^{19} \text{ m}^{-3} \).

**Figure 9.** 2D distributions of the force balance of \( |V_{\text{fric}}| - |V_{\text{ther}}| \) between the friction and thermal forces for the equilibrium cases (a), (b) and the perturbed cases (c), (d) by EMC3-EIRENE modeling at the toroidal angle of \( \varphi = 0^\circ \) \( (D_{\perp} = D_{\text{imp}} = 0.4 \text{ m}^2 \text{ s}^{-1} \) and \( \chi_{\perp} = 2.0 \text{ m}^2 \text{ s}^{-1}) \). The low \( n_u = 0.73 \times 10^{19} \text{ m}^{-3} \) is used in (a), (c) and high \( n_u = 1.5 \times 10^{19} \text{ m}^{-3} \) in (b), (d).
Figure 10. Profiles of respective W ions amounts inside and outside the separatrix for RMP and no RMP cases (a) and W ions amount ratios between RMP and no RMP cases inside and outside the separatrix for different $n_u$ (same $\chi_\perp = 2.0 \text{ m}^2 \text{s}^{-1}$ for both RMP and no RMP cases). The normalized poloidal magnetic flux ($\psi_N = 1.0$) is treated as the position of the separatrix. The regions ($\psi_N < 1.0$ and $\psi_N > 1.0$) mean inside the separatrix and outside the separatrix, respectively.

Figure 11. Profiles of W ions amounts under RMP application (a) and W ions amount ratio between RMP and no RMP cases (b) with $n_u = 0.73 \times 10^{19}, 1.0 \times 10^{19}, 1.25 \times 10^{19}$ and $1.5 \times 10^{19} \text{ m}^{-3}$ against $D_{\text{imp}}$ (same $\chi_\perp = 2.0 \text{ m}^2 \text{s}^{-1}$ for both RMP and no RMP cases).

much larger compared to low $n_u$. This is also due to the strong change in W physical sputtering yield for high $n_u$ induced by the difference in edge plasma temperature between same and individual $\chi_\perp$.

For shot #67578 ($n_u = 0.73 \times 10^{19} \text{ m}^{-3}$), the difference in W sputtering flux between RMP and no RMP cases makes a minor contribution to the significant decrease in W emission due to the small reduction (10%–15%) in the W sputtering flux for RMP case. The above analysis shows that RMP-induced variation of edge plasma temperature causes a more obvious difference in the W sputtering flux between RMP and no RMP cases for low edge plasma temperature due to the sensitive dependence of physical sputtering yield. The strong decrease in the W sputtering flux for low edge plasma temperature under RMP application is beneficial to control the W influx to edge plasma.

3.3. Tungsten edge transport

The space-integration of W ions inside the simulation domain has been performed according to EMC3-EIRENE modeling results, which is defined as W ions amount in the following analysis. In order to merely study the impacts of RMP fields on W ions amount, the influence of the difference in W sputtering flux as discussed above should be excluded. Hence, the W ions amounts and densities as shown below have been normalized by the W sputtering flux for RMP and no RMP cases. Figure 8(a) displays the W ions amount with and without RMP applications for different $n_u$. The W ions amounts are calculated by sum over all W ionization states. The increase in $n_u$ results in an enhanced impurity screening effect and a reduced W ions amount for both RMP and no RMP cases. Figure 8(a) shows that the friction force becomes stronger for high $n_u$ for both cases. Hence, the enhanced friction force can effectively reduce W
strong thermal force can push W ions into the perturbed separatrix by perpendicular transport as shown in figure 3. The stochastic field lines can serve as pathways for W ions transport into the perturbed separatrix. While for the equilibrium field, the W ions mainly transport along stochastic magnetic geometry inside the perturbed separatrix where has a low leakage and resulting W ions amount as shown in figure 8 (a). In addition, for the same \( n_u \), the edge plasma temperature is higher for the same \( \chi_\perp \) which results in a stronger thermal force for the same \( \chi_\parallel \). Hence, the W ions amounts are higher for the same \( \chi_\perp \) in comparison with the individual \( \chi_\perp \) as shown in figure 8(a).

The W ions amount ratios between RMP and no RMP cases for different \( n_u \) are presented in figure 8(b) to study the changes in W edge transport behavior induced by RMP fields. It is found that RMP application leads to a different W impurity screening behavior for low and high \( n_u \). For \( n_u = 0.73 \times 10^{19} \text{ m}^{-3} \), the W ions amount for RMP case is about 50% higher than no RMP case. While the W ions amount for RMP case reduces by around 50% compared to no RMP case for \( n_u = 1.5 \times 10^{19} \text{ m}^{-3} \). A detailed analysis of respective W ions amounts inside and outside the separatrix has been conducted to study the altered W impurity screening behavior for different \( n_u \).

Figure 10(a) presents the respective W ions amounts inside and outside the separatrix for RMP and no RMP cases. In view of small difference between same and individual \( \chi_\perp \) in figure 8, the same \( \chi_\perp = 2.0 \text{ m}^2 \text{ s}^{-1} \) is employed for both RMP and no RMP cases henceforth. It is seen that the individual W ions amounts inside the separatrix for RMP and no RMP cases are higher than that outside the separatrix in figure 10(a). Figure 10(b) displays the individual W ions amount ratios between RMP and no RMP cases inside and outside the separatrix. The application of RMP fields breaks the original flux surfaces of the equilibrium fields, which results in a stochastic magnetic geometry inside the perturbed separatrix as shown in figure 3(b). The stochastic field lines can serve as pathways for W ions transport into the perturbed separatrix. While for the equilibrium field, the W ions mainly transport into the unperturbed separatrix by perpendicular transport as they reside upstream. For low \( n_u = 0.73 \times 10^{19} \text{ m}^{-3} \), the strong thermal force can push W ions into the perturbed separatrix along stochastic pathways more easily for RMP case, which leads to an increase of 70% in the W ions amount inside the perturbed separatrix compared to no RMP case in figure 10(b). Meanwhile, the W ions amount outside the perturbed separatrix reduces by about 20% than that outside the unperturbed separatrix. On the other hand, the friction force is enhanced in the edge plasma when \( n_u \) increases as shown in figure 9. The W ions inside the perturbed separatrix are more readily driven back to divertor targets through the stochastic pathways for RMP case, which causes that the W ions amount inside the perturbed separatrix decreases strongly as shown in figure 10. Therefore, more remarkable screening effect of W impurity is obtained for high \( n_u \) under RMP application in figure 8(b).

The studies of carbon impurity transport on EAST [20] and LHD [9, 39] show that the enhanced impurity perpendicular transport plays an important role in interpreting the experimental observations for stochastic magnetic topology. Further, the recent experiments on DIII-D demonstrates that the RMP fields can lead to an increased impurity diffusion in the pedestal region [47]. Hence, the parameter scan with larger \( D_{\text{imp}} \) has been performed here to check its impact on W transport behavior under RMP application. Figure 11(a) presents W ions amounts under RMP application against \( D_{\text{imp}} \) for different \( n_u \). As is seen that the increased \( D_{\text{imp}} \) leads to a reduced W ions amount for different \( n_u \).

The 2D distributions of W ions density for \( D_{\text{imp}} = 0.4 \) and \( 3.5 \text{ m}^2 \text{ s}^{-1} \) are displayed in figure 12. It is noted that the maximum of color bar in figure 12(b) is an order of magnitude lower than that in figure 12(a). For low \( D_{\text{imp}} \), the W ions mainly populate inside the perturbed separatrix with long \( L_c \) as shown in figure 12(a). For high \( D_{\text{imp}} \), the loss fraction of W ions inside the perturbed separatrix becomes stronger, which cannot be compensated by W ions penetration outside the perturbed separatrix where has a low \( L_c \) and W density. This leads to a reduced W ions amount inside the perturbed separatrix in figure 12(b). Therefore, the enhanced perpendicular migration of W ions results in a decreased W ions amount as shown in figure 11(a).

The W ions amount ratios between RMP and no RMP cases against \( D_{\text{imp}} \) are presented in figure 11(b). Here it is noted that the enhanced \( D_{\text{imp}} \) is merely employed for RMP cases. It is seen that the W ions amount ratio decreases strongly as \( D_{\text{imp}} \) increases. The W ions amount ratios are mainly below 0.3 for different \( n_u \) when \( D_{\text{imp}} \) is higher than 1.5 \text{ m}^2 \text{ s}^{-1}. This indicates that the increase in \( D_{\text{imp}} \) can suppress the W ions amount under RMP application compared to the equilibrium case. For low \( n_u = 0.73 \times 10^{19} \text{ m}^{-3} \), the effect of enhanced perpendicular transport of W ions overwhelms the effect of thermal force for parallel transport, which also leads to a good W ions screening effect for RMP case. Hence, the enhanced perpendicular transport presumably plays an important role in interpreting the substantial reduction in W emission under RMP application for shot #67578. The above results demonstrate that the scenarios with high edge plasma density and enhanced perpendicular transport show a good W impurity screening effect for RMP case.
4. Summary

The impacts of the application of RMP fields on the tungsten sputtering and transport properties have been studied with EMC3-EIRENE code. The W sputtering flux has been evaluated under RMP and no RMP applications according to EMC3-EIRENE simulation results. For low edge plasma density, the high deuterium impact energy leads to a small reduction in the W sputtering flux for RMP case in comparison with no RMP case. While for high edge plasma density, a more obvious difference in the W sputtering flux between RMP and no RMP cases is emerged due to the sensitivity of W sputtering yield on deuterium impact energy. Therefore, the RMP application for high edge plasma density can efficiently suppress the W sputtering flux into edge plasma. In addition, the uncertainty in the edge plasma temperature under RMP field induces a larger variation range of the W sputtering flux difference for high edge plasma density. The detailed analysis of W ions amount has been performed with RMP and without RMP applications. With the small impurity perpendicular transport coefficient, the edge plasma exhibits a better W ions screening effect for high edge plasma density. For the enhanced tungsten perpendicular transport, the difference in the W ions amount indicates a reduced dependence on the edge plasma conditions, i.e. all cases show a good W ions screening effect under RMP application.

Due to diagnostic limitation on the measurements of W emission, it is difficult to give a definite interpretation on the dramatic reduction in the tungsten emission for shot 675758. However, based on the present study, it can be speculated that the enhanced tungsten perpendicular transport is not a trivial reason for the observed decrease in W emission due to small reduction (10%–15%) in tungsten sputtering flux under RMP fields. Further, according to the current simulation, one can see that RMP application with high edge plasma density condition is preferential for EAST discharges due to reduced tungsten sputtering flux and good tungsten screening effect.

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