Tskhakaya, D.; Groth, Mathias; Contributors, JET EFDA

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1D kinetic modelling of the JET SOL with tungsten divertor plates

D. Tskhakaya, M. Groth, JET EFDA contributors

1JET-EDFA, Culham Science Centre, OX14 3DB Abingdon, UK
2Association EURATOM-ÖAW, University of Innsbruck, Technikerstrasse 25/II, A-6020 Innsbruck, Austria
3Aalto University, Association EURATOM-Tekes, Otakaari 4, 02015 Espoo, Finland

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ABSTRACT

In this work a fully kinetic model of the JET SOL with tungsten divertor plates has been developed. It includes the dynamics of main-ions (D+) and electrons, the neutrals (D, C, W) and the impurity particles (Cm+, Wn+). Our simulations show extremely low concentration of W impurity. We identify two reasons which are responsible for this effect: (1) for low temperature divertor plasma the energy of most of the main-ions and the impurities in a low-ionization state impinging the divertor plates is below the W-sputtering threshold energy; (2) with increasing temperature the W-sputtering increases, but the potential drop across the divertor plasma increases too, so that most of the W ions are reabsorbed at the divertors.

1. Introduction

Tungsten is becoming a common divertor material for our day and future tokamaks. As a result, the development of the corresponding SOL models has become one of most important topics in fusion plasma research. In the present work we model tungsten generation and transport along the field lines in the JET SOL using fully kinetic approach: the plasma (e, D+), the neutral (D, C, W) and the impurity (Wn+, Cm+) particles are treated kinetically.

The simulations of this type are extremely CPU-intensive. There are several reasons for using such modeling. It has been demonstrated that kinetic effects can dominate in the high recycling plasma even if there are only common impurities like carbon (see references there). Introduction of massive high-Z impurities complicates the problem, so that the kinetic effects can become essential. Here we mention two additional effects.

First of all, massive high-Z impurities (like tungsten) cannot be treated as trace impurities. E.g. the friction force between different ionized states of W, \( R_{W^nW^{n'}} \), can be of the same order as the friction force between W and main D ions, \( R_{W^+D^+} \) [6]:

\[
\sum_{n=k} R_{W^nW^{n'}} / R_{W^+D^+} \sim \sqrt{M_W/M_D} \approx 10 \sum_n n^2 c_{W^n} \approx 10 \sum_n n^2 c_{W^n}, \tag{1}
\]

where \( M_{W,D} \) are particle masses and \( c_{W^n} \) is the \( W^n \) concentration. As we see, if \( \sum_n n^2 c_{W^n} \sim 0.1 \), then the friction force between W ions cannot be neglected. We note that due to lower mass ratio this effect is practically negligible for light impurities.

The second effect is related to the tungsten sputtering, which is strongly coupled with the divertor plasma parameters and extremely sensitive to the energy of ions impinging at the divertor plates. It is usually assumed that these ions are accelerated in a constant (in time) sheath potential drop \( \sim 3T_e/e (T_e \text{ is the electron temperature}) \). In reality the potential oscillates around this average value, which may accelerate resonant ions up to energies more than \( 3T_e \). In Fig. 1 is plotted the oscillation spectrum of the potential at the magnetic presheath entrance in the outer divertor plasma (the divertor potential is set to zero). The maximum at low frequency is near to \( C \) cyclotron and the other two correspond to the lower and upper hybrid wave frequencies [7]:

\[
\omega_{LH,\perp} = \sqrt{\left( \omega_e^2 + \omega_p^2 \right) / 2 \pm \sqrt{\left( \omega_e^2 + \omega_p^2 \right)^2 / 4 - \omega_e^2 \omega_p^2 \sin^2 \theta}} \tag{2}
\]

where \( \Omega_e \) and \( \Omega_p \), the electron cyclotron and plasma frequencies; \( \theta \) is the angle between the magnetic field and the divertor surface. Although the amplitude of these oscillations is lower than the average potential \( \sim 110 \text{ eV} \), it is not obvious that the additional energy gain by resonant ions is negligible. Moreover, the tungsten atoms can be ionized near to the divertor plates and the probability to return back to the plates strongly depends on the electric field (and its oscillations) in the sheath. As we will see below, exactly this reposition is responsible for significant reduction of the effective W-sputtering yield.
The plasma, the neutral and impurity particles are treated in 1D-3V, 2D-3V and quasi-2D-3V approximations, respectively ($n_\text{impurity}$). The impurity particles are assumed to be isotropically scattered. We extrapolated the cross-sections according to the expression [13]:

$$\sigma = \frac{A \ln(E) + B}{E}$$

The obtained cross-sections are plotted in Fig. 3. The after-collision electrons are assumed to be isotropically scattered.

Implementation of PSI processes. Contrary to the ionization cross-sections there is a large spread in tungsten-related PSI data. E.g. the tungsten self-sputtering yield given in [9] is too large...
and results, according to our test simulations, in unphysically high W concentrations. During the simulation W density reached $0.5 \times 10^{20}$ m$^{-3}$ and was rapidly increasing, so we stopped the run. Eckstein in [10] proposes more realistic sputtering yields (see Fig. 4), which are implemented in the BIT1. Unfortunately, in [10] the W sputtering yields due to carbon impact are missing, hence we used the data from [9] with the corrected threshold energy (45 eV) considered in [14].

The probability that after ionization the sputtered W returns back to the divertor strongly depends on the distribution of sputtered W atoms. Hence, we implemented the following sputtered-W-distribution model. For D and W impact we use the fit function from [15]:

$$f_w(E) = \frac{2a^2E_0E_0}{(E + E_0)^3} \quad a = 1 \pm \frac{(M_1 + M_2)^2E_s}{4M_1M_2}$$

where $M_1$ and $M_2$ are the atomic masses of the target and projectile atoms (ions); $E_0$ and $E_s$ are the surface binding and impinging+ particle energies. For the C induced W sputtering we use a simple model:

$$f_w(E) = \begin{cases} \text{const.} & \text{for } E \leq E_{\text{max}} = 10 \text{ eV}, \\ 0, & \text{for } E > E_{\text{max}}. \end{cases}$$

The angular distribution for the both models is the “cosine” one: $\cos(\alpha) = \sqrt{\text{RandomNumber}}$, where $\alpha$ is the angle between the velocity of injected W and the normal to the divertor plate.

During the simulation we use 60,000 cells along the poloidal direction. This allows finest resolution in space down to the Debye length and electron gyro-radius. Each run took in average 20,000 CPU hours on 1024 processors, all together (including test runs) about 300,000 CPU hours have been consumed.

3. Simulation results

During the simulations we adjust the plasma and the heat source parameters to match the experimentally observed upstream SOL density, $n_u$, and electron temperature, $T_{e,u}$. For reference we consider the shots #81472, #81478 and #81484 with $n_u = 1.5 - 1.8 \times 10^{19}$ m$^{-3}$, $T_{e,u} = 45 - 75$ eV. Simulation parameters were chosen in a way to match these upstream data. We made three sets of simulations:

1. High temperature case ($T_{e,u} > 65$ eV) with relatively strong heat source.
2. Low temperature case ($T_{e,u} \sim 45$ eV) with 2.5 times weaker heat source.
3. The case as 1. with the additional injection of $100$ eV C$^{++}$ ions from the particle source. In this way we simulate influx of hot carbon ions from the pedestal.

Low temperature carbon particles originating from different plasma-facing-components are modeled via injection of C atoms from the divertors with the fixed flux $10^{21}$ m$^{-2}$s$^{-1}$. C atoms are assumed to be in thermal equilibrium with Franck–Condron distributed D atoms and have the temperature 2 eV.

Typical profiles of density and temperature obtained from the simulation are plotted in Fig. 5, indicating low concentration of W particles (in different ionized state). To estimate the concentration of W ions we consider the “W-related” Z-effective:
We did not observe W ions with ionization state more than 4. These results can be explained after analyzing of divertor plasma parameters from Table 1. As we can see, with increasing upstream temperature increases potential drop across the divertor plasma. For low temperatures the energy of D and C ions hitting to the divertor plates is too low to sputter sufficient amount of W. With increasing energy the W sputtering increases, but the potential drop in the divertor plasma increases too. As a result, most of the W atoms are ionized in the vicinity of the divertor and return back to the plates. There are two effects leading to the observed prompt redeposition of W ions: first is the “near-divertor” ionization of W due to low ionization potential 7.86 eV (for comparison the ionization potentials for D and C are 13.6 and 10.6 eV), second, W ions have large Larmor radius ~2 nm, so that they are redeposited within the distance of a Larmor radius. Important to note that a significant fraction of W ions escaping this prompt redeposition are returned back due to the friction with the main ions.

Our simulations indicated that the accuracy of \( n_{\text{min}} \approx 1 \times 10^{15} \text{ m}^{-3} \) is not sufficient for studying of the distribution of W charge states in the upstream SOL. These will be addressed in our future work.

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References

[18] G.J. van Rooij, This Conference.

4. Conclusions

Our simulations confirm experimental observations that W net erosion represents only tiny fraction (in our simulation ~1%) of the W gross erosion. The estimated upstream W fluxes, \( F_{\text{upstream}}^{W} \), are in good agreement with the experimentally observed values \( \lesssim 1 \times 10^{15} \text{ m}^{-2} \text{ s}^{-1} \) [16]. Moreover, this value is not very sensitive to the divertor plasma temperature. For low temperatures the energy of D and C ions hitting to the divertor plates is too low to sputter sufficient amount of W. With increasing energy the W sputtering increases, but the potential drop in the divertor plasma increases too. As a result, most of the W atoms are ionized in the vicinity of the divertor and return back to the plates. There are two effects leading to the observed prompt redeposition of W ions: first is the “near-divertor” ionization of W due to low ionization potential ~7.86 eV (for comparison the ionization potentials for D and C are 13.6 and 10.6 eV), second, W ions have large Larmor radius ~2 nm, so that they are redeposited within the distance of a Larmor radius. Important to note that a significant fraction of W ions escaping this prompt redeposition are returned back due to the friction with the main ions.