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

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A B S T R A C T

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 the 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 [1–5] and 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+n,W−n, can be of the same order as the friction force between W and main D ions, R W−D, [6]:

$$\sum_{n=\pm1} R_{W+n,W-n} / R_{W-D} \approx \sqrt{M_W / M_D} \approx 10 \sum_{n=\pm1} n^2 c_{W-n},$$

where $M_{W,D}$ are particle masses and $c_{W-n}$ is the Wn+ concentration. As we see, if $\sum_{n=\pm1} n^2 c_{W-n} \approx 0.1$, 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 $3T_e/e$ (Te 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]:

$$\omega_{\text{LH}} = \frac{\Omega_e^2 + \Omega_p^2}{2} \pm \sqrt{\left(\frac{\Omega_e^2 + \Omega_p^2}{4}\right)^2 - \frac{\omega_p^2}{4} \sin^2 \theta},$$

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 ($\sim 110$ 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 redeposition is responsible for significant reduction of the effective W-sputtering yield.
trix and to the outer wall (see Fig. 2). The plasma, the neutral and impurity particles are treated in 1D3V, 2D3V and quasi-2D3V approximation, respectively (\(n<11\) and \(n<7\), respectively. The corresponding cross-sections are taken from [11,12]. Some of cross-sections are given for energies below 1 keV. In this case 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 \(0.5 \times 10^{20} \text{ m}^{-3}\) 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]:

\[
f_w(E) = \frac{2a^2 E_i E}{(E + E_i)^3} \quad a \equiv 1 + \frac{(M_1 + M_2)^2 E_s}{4M_1 M_2 E_0},
\]

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 Debey 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 \(n_u \approx 1.5-1.8 \times 10^{19} \text{ m}^{-3}\), \(T_{e,u} \approx 45-75 \text{ eV}\). Simulation parameters were chosen in a way to match these upstream data. We made three sets of simulations:

1. High temperature case (\(T_{e,u} \approx 65 \text{ eV}\) with relatively strong heat source.
2. Low temperature case (\(T_{e,u} \approx 45 \text{ eV}\) with 2.5 times weaker heat source.
3. The case as 1. with the additional injection of \(100 \text{ eV} C^{++}\) 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 \(10^{23} \text{ m}^{-2} \text{s}^{-1}\). C atoms are assumed to be in thermal equilibrium with Franck–Condon 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:

![Fig. 4. W-sputtering yield for normal impact of different particles. (a) W self-sputtering yield from different sources; (b) yields implemented in the BIT1 code.](image)

![Fig. 5. Poloidal profiles of the density (a) and the temperature (b) in the SOL for the case 1.](image)
Moreover, with the given resolution, at the distances more than 1 cm from the divertor plates is negligible. The corresponding result, only a very tiny fraction of sputtered W can escape reab- sorption and propagate to the upstream SOL. The corresponding diffusion, 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 \(\sim 2/\text{m} \text{nm}\), 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 \(n_{\text{min}} \sim 10^{15} \text{m}^{-3}\) 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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