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Kinetic Effects in ITER Scrape-off Layer

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ABSTRACT

The divertor targets in tokamaks are constantly bombarded with high-energy neutral and charged particles and such violent events can pose a serious threat to the long-time resistance of the divertor materials. The wall erosion, caused by the bombardment, releases impurities, that migrate towards the bulk plasma and due to the effects, the plasma state is deteriorated. In order to keep the limits of wall erosion, it is important to estimate the plasma characteristics in the Scrape-off Layer (SOL) i.e the region outside the last closed magnetic surface (separatrix). However, the transient heat loads such as ELMs (Edge-Localized modes) occur in tokamak edge during H-mode confinement lead to a significant loss of stored plasma energy. Once the ELM-driven plasma pulse has crossed the magnetic separatrix, it travels mainly parallel to the magnetic field lines and ends up hitting the divertor plate.

This contribution describes the first results of efforts to address this issue for ITER simulations under high-performance conditions using the 1D3V electrostatic parallel Particle-in-Cell (PIC) code BIT1 during ELM-free or no-ELM. As a first approximation plasma-surface interaction processes are not included in this model. The burning plasma conditions correspond to the ITER Q = 10, 15 MA baseline at q_{95} = 3, for which the poloidal length of the 1D SOL is 20 m from inner to outer target. Typical upstream separatrix parameters of $n_e \sim 3 - 5 \cdot 10^{19}$ m^{-3}, $T_e \sim 100 - 150 eV$, and $T_i \sim 200 - 300$ eV are assumed, guided by SOLPS-ITER code runs. Inclined magnetic fields at the targets of ($\sim 5°$) are included, as are the particle collisions, with a total of $3.4 \cdot 10^5$ poloidal grid cells giving shortening factors of 20. In these simulations, for the first time, the neutrals are included but the impurities are neglected. A typical simulation requires up to 60 days running massively parallel 1152-2304 cores of the EU Marconi super-computer.

1 INTRODUCTION

The large heat load on the divertor plate, is one of the main challenges that is constituted for the future tokamak operation, such as ITER. The divertor surfaces are constantly bombarded with high-energy neutral and charged particles and may thus see their lifetime considerably reduced. The erosion, caused by the bombardment of the particles on the divertor, also releases impurities, which migrate towards the bulk plasma and, due to radiation, deteriorate its confinement [1]. In order to keep the limits of the wall erosion, it is important to estimate the plasma characteristics in the scrape-off layer (SOL) i.e the region outside the last closed magnetic surface (separatrix). Most of the studies are focused on the problem of the transition between a hot plasma and a material surface, both for unimagnetized and magnetized plasmas [2]. The layer between the plasma and the wall i.e divertor targets is called plasma-wall transition (PWT) [2].

However, transient events such as edge-localized modes (ELMs) occur in tokamak edge during H-mode confinement. ELMs are plasma relaxations, presumably of MHD origin, which cause a sudden drop in density and temperature of the pedestal plasma, leading to a significant loss of the stored plasma energy. Once the ELM-driven plasma pulse has crossed the magnetic separatrix, it travels mainly parallel to the magnetic field lines and ends up hitting the divertor plate. Such violent events can pose a serious threat to the long-time resistance of the divertor materials [3, 4, 5].

The SOL is a complex region where a multitude of physical and chemical processes take place. The low collisionality of the plasma, different inelastic and short time scale processes, and geometrical effects in this region can cause deviation of the parallel transport from the classical one. Hence, development of the realistic kinetic models in the SOL is of top importance. Usual tools for the SOL study represent large fluid codes, where a number of kinetic effects are implemented manually [6, 7]. These effects represent the boundary conditions in regions of plasma-surface interaction and the limiting expressions for the parallel heat flux and viscosity. The formulation of boundary conditions (BCs) and their time dependence is an interesting and important task for plasma edge studies [8]. To estimate BCs several kinetic simulations need to be done [9].

The aim of this work is to derive BCs at the PWT of the stationary (ELM-free) state from the kinetic simulation in ITER tokamak including the neutrals in the simulation system.

2 THEORY

The PWT strongly affects the particle and heat fluxes to the wall, thus influencing all plasma-surface interaction (PSI) processes. In fusion plasma devices the impinging-particle energies and flux rates define the lifetime of plasma-facing components. As a consequence, investigations of the PWT have become a genuine branch of plasma physics. In describing the electrostatic magnetised PWT it is usually assumed that $\lambda_D << \rho_i << L$, where λ_D, ρ_i and L are the Debye length, the ion Larmor radius, and the charged neutral particle collision mean free path (or characteristic size of the plasma in front of the wall), respectively [3, 9]. Under these conditions, the PWT can be divided into the following three parts: the Debye sheath (DS), the magnetic presheath (MP), and the collisional presheath (CP) (Fig. 1). In the CP, where collisional processes are dominating, ions are accelerated to the sound speed. In the MP Lorentz forces start to dominate, but plasma is still quasineutral. In the DS the electric field is so strong that plasma becomes non-neutral. In the present work we unify two layers adjacent to the wall, the DS and MP, and call it the plasma sheath [9].

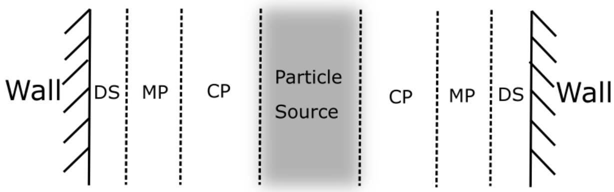

Figure 1: Plasma wall transition parts

The classical model of the combined DS-MP region neglects cross-field drifts and assumes the electron velocity distribution to be a cut-off Maxwellian and the ion distribution to be a shifted Maxwellian. Then, using the particle and energy flux-conservation equations and the Bohm-Chodura condition, one can obtain the BCs at the plasma sheath and at the wall [9].

The boundary conditions must be provided at the sheath entrance. Because the sheath entrance is not clearly defined point, to measure the conditions is sufficiently difficult. To define the point a number of conditions should be fulfilled [6, 9, 10]:

1. The fixed point (sheath entrance) has a specified number of Larmor radii ($x = N\rho_i$);

2. The last point where the ion and electron charge densities become equal, defines the sheath edge according to the quasineutral condition ($n_e = n_i$);

3. The point where the ion and electron fluxes become equal, defines the sheath edge according to the ambipolar current condition ($n_e V_{\|e} = n_i V_{\|i}$);

4. The last point in front of the divertor where (under the driftless approximation) ions travel parallel to the magnetic field, $V_{xi} = V_{\|i} sin\Theta$, defines the sheath edge according to the magnetized ion condition, where $\Theta = B_x/B$ is the ratio of the poloidal magnetic field to the total field strength and V_x is the flow velocity projected in the poloidal direction respectively;

5. The point where the ion fluid velocity exceeds the sound speed $V_{\|i} \geq C_s$ defines the sheath edge according to the Bohm condition.

Thus, establishing realistic boundary conditions (BCs) at the MP entrance (MPE) is becoming of top importance. The main parameters needed for BCs at the MPE are as follows: the potential drop between the MPE and the wall ($\Delta\phi$), the ion fluid velocity component $\left(V_{\|}^{i}\right)$, and the electron and ion energy fluxes $\left(Q_{sh}^{e,i}\right)$. Those quantities are calculated from a set of equations (1) [3, 6, 9, 10]:

$$M = \frac{V_{\|}^{i}}{C_s}; \quad \gamma^{e,i} = \frac{Q_{sh}^{e,i}}{\Gamma^{e,i} \cdot T^{e,i}}; \quad \varphi = \frac{e\Delta\phi}{T^e}; \tag{1}$$

where M, $C_s = \sqrt{\frac{Te+\delta_i T_i}{m_i}}$, $\gamma^{e,i}$, $\Gamma^{e,i}$ and φ are the Mach number, the ion-sound speed, the electron and ion sheath heat transmission factor, the electron and ion fluxes to the divertor, and the normalized potential drop, respectively. $m_{e,i}$ and $T_{e,i}$ are electron and ion masses and electron and ion temperature. Here δ_i (~ 1)is the polytrophic constant.

The classical boundary conditions at the plasma-wall interface are formulated using the sheath theory:

$$M = 1; \quad \varphi = ln\left[\sqrt{\frac{m_i}{2\pi m_e}}\frac{1}{\sqrt{1+T_i/T_e}}\right] \quad \gamma_e^{sh} = \gamma_e^{w} + \frac{\Delta\phi}{T_e}; \quad \gamma_i^{sh} = \gamma_i^{w} - \frac{\Delta\phi}{T_i}; \tag{2}$$

where $\gamma_{e,i}^{sh}$ and $\gamma_{e,i}^{w}$ are sheath heat transmission factors of the electron and ion at the sheath and wall. So at the point where $M = 1$, the $C_s = V_{\|}^{i}$ and $\varphi \sim 3$. Under steady-state conditions, distribution of the particle and energy fluxes on the wall for electrons are half Maxwellian. After integration the sheath transmission coefficients at the wall are: $\gamma_e^w \sim 2$ and $\gamma_i^w \sim 6 - 7$, and the sheath transmission coefficients at the sheath are $\gamma_e^{sh} \sim 5$ and $\gamma_i^{sh} \sim 3 - 4$. From the sheath transmission coefficients it can be concluded that the sheath acts as an electron energy filter. The sheath, therefore, applies a powerful cooling effect to the electrons. It is important to distinguish between the electron power flux received by the surface, which is the surface heating power due to the sheath, and the power flux lost by the plasma electron population, which we can call the electron cooling power because of the sheath (Fig. 2) [3].

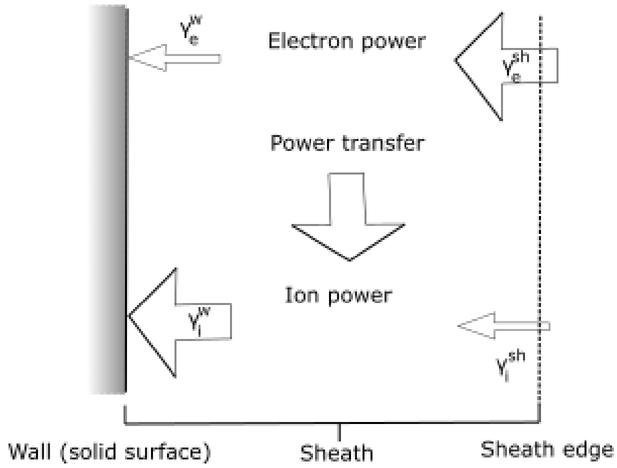

Figure 2: The sheath mechanism for transferring power

3 SIMULATION GEOMETRY

BIT1 is an electrostatic massively parallel Particle in Cell (PIC) code for simulation of plasma edge. It incorporates $e, H, H_2, He, C, O_2, W,$ their isotopes and few hundreds of corresponding AMS processes. The number of implemented particle types is limited by available AMS data: searching for and validating of the corresponding differential cross-sections and of the plasma-surface interaction (PSI) data is one of the most time consuming part in development of realistic plasma edge models. The collision operators simulate atomic and molecular processes, conserving energy and momentum. The PSI represents a linear model with prescribed (energy and angular dependent) particle release coefficients and prescribed velocity distributions of particles released from the wall [11]

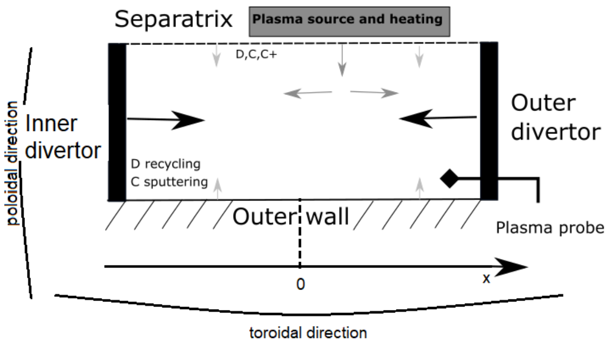

Figure 3: BIT1 simulation geometry

The Simulation geometry corresponds to a $1D$ flux tube in the SOL along the poloidal direction (see Fig. 3, [8]). The plasma and heat source model the cross-field transport across the separatrix. The center and the length of the source region correspond to the OMP (outer midplane) and to the distance from x-point to x-point along the separatrix. Plasma particles (electrons and D^+ ions) entering the system propagate towards the divertor plates, where they are absorbed (except low energetic electrons which might be reflected by the sheath potential) at the divertor plates. The absorbed ions might sputter C impurity or recycle D atoms, which propagate upstream in the SOL and interact with plasma [12].

The sputtering (physical and chemical) and recycling coefficients are energy and angle dependent. The neutrals are treated in $2D$ geometry: if they reach the radial boundaries, corresponding to the private region and the outer wall, they are removed from the simulation. The impurity ions (C^+) might be removed from the simulations with a probability corresponding to the (specified) cross field diffusion. In order to keep these outfluxes ambipolar, one electron is removed together with the C^+ ion.

Input file of the original BIT1 code is extremely complex. It includes the description of geometry of the SOL, the description of the external circuit, the description of particle sources, the description of the simulated species, description of the atomic and molecular physics, physics surface interaction processes for each particle species, code specific parameters, e.g. number of cells, and so on. This general input is very flexible and allows testing of different plasma edge models.

In this case, were performed for burning plasma conditions corresponding to ITER, for which the poloidal length of the 1D SOL is $\sim 20\ m$ from the inner to the outer target. Typical upstream separatrix parameters of $n_e \sim 3{-}5 \cdot 10^{19}\ m^{-3}$, $T_e \sim 100{-}150\ eV$ and $T_i \sim 200{-}300\ eV$ are assumed, guided by SOLPS-ITER code runs [13]. Inclined magnetic fields at the targets of ($\sim 5°$) are included, as are the particle collisions, with a total of $3.4 \cdot 10^5$ poloidal grid cells giving shortening factors of 20.

For these simulations the secondary electron emission at the tungsten targets is neglected and also the impurities are not included. A fully independent run was performed, which means that we started with an empty system and reached the stationary state. Based on the previous research [14, 15, 16] where the simulations were performed without neutrals here we have added a neutrals in to the simulation system. A standard BIT1 simulation runs for about 90 days in parallel computing mode on 1152-2304 computer cores.

4 SIMULATION RESULTS

We have saved the plasma state from the previous simulations [14, 15] we and have added the neutrals. The peaking values of the electron, $305\ eV$, and ion temperature, $423\ eV$, as well as the electron and ion density, that are equal to $4.2 \cdot 10^{20}\ m^{-3}$, are obtained at the outer mid-plane (OMP), close to $12\ m$ on poloidal direction from the inner divertor. The plasma is quasineutral in all the SOL except the narrow Debye sheath in front of the divertor plates. Also the plasma potential is peaking at the OMP reaching $800\ V$ there. The ion and electron parallel velocities, as well as, a densities are equal. The peaking values of the neutral temperature is $350\ eV$ and neutral density is $5 \cdot 10^{20}\ m^{-3}$. The neutral densities values peaks at the divertors due to the neutralisation of the ions on the divertors. The profiles are presented in [16]

When the simulations are completed, we have obtained the plasma sheath point on the densities profiles, based on the conditions explained in section 2. It is obvious that (Fig. 4) the length of the PWT is from $1.3 \cdot 10^{-3}$ m to $2.7 \cdot 10^{-2}$ m. DS point is $1.3 \cdot 10^{-3}$ m, MP $1.7 \cdot 10^{-2}$ m and CP $2.7 \cdot 10^{-2}$ m, so the length of the plasma sheath is $1.7 \cdot 10^{-2}$ m or $3.4\rho_i$, where ρ_i is ion gyroradius. From the Fig. 4 can been seen that the plasma at MP and CP is quasineutral, while at the DS, the electric field is so strong that plasma becomes non-neutral.

We determinate the values of T_e, T_i, $V_{\parallel}^i$ from the profiles in [16], at the plasma sheath . Then from Eq. 1, the BCs are calculated and the results are presented in Table. 1. Particle and heat fluxes are calculated from the wall diagnostics of the BIT1 code.

The sheath parameters obtained from the simulation results done in this work do not deviate drastically from the classical i.e theoretical one [8].

Based on the previous research [14] where the BCs are obtained without neutrals, also here during the time of ELM-free or no-ELM $10\mu s$ the values of Mach number and the sheath transmission coefficients for electrons and ions are constant and near to theoretical in [8]. So

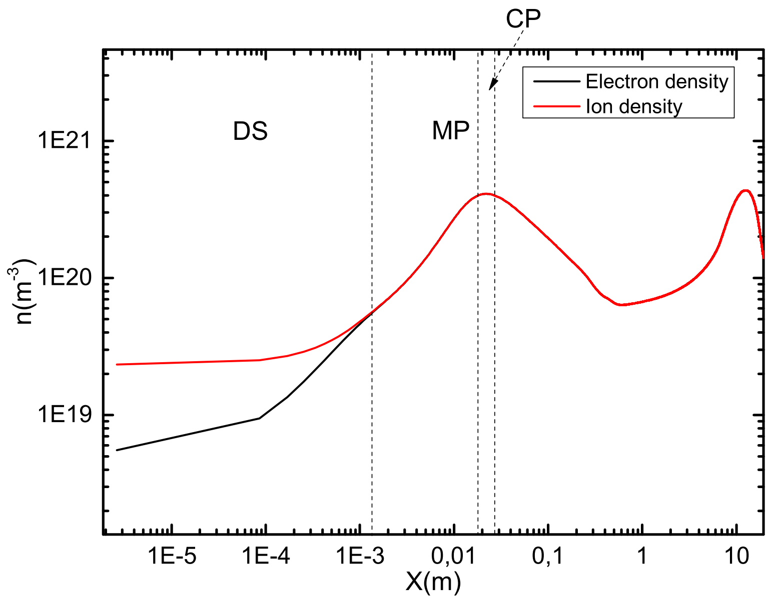

Figure 4: Debye sheath (DS), magnetic presheath (MP) and collisions presheath (CP) of ITER case

Parameters	Theoretically	Experimentally
T_e		75 eV
T_i		108 eV
$V_{\parallel}^{i}$		$2 \cdot 10^4$ m/s
M	1	0.8
$\Delta\phi$ inner div.	236 V	240 V
$\Delta\phi$ outer div.	236 V	243 V
φ inner div.	3	3.04
φ outer div.	3	3.07
γ_e wall	2	2.1
γ_e sheath	5	4.9
γ_i wall	6	5.9
γ_i sheath	3	2.8

Table 1: BCs theoretical and experimental values

this method for calculating the BCs is acceptable and will be used in future work. In the future the BCs for Type-I ELM and post-ELM will be simulated and calculated.

5 CONCLUSION

Kinetic effects in the SOL play an important role for the future fusion devices: they strongly affect plasma and power loads to the plasma facing components (PFC) and therefor influence the lifetime of the PFCs. The, kinetic study of the SOL is one of the most challenging topics in fusion plasma research. For a systematic kinetic study of SOL, the unique PIC/MC code BIT1 was used in this study. The BIT1 code contains the full range of SOL kinetic parameters needed to run a set of 1D SOL simulations. The model of SOL in the fluid codes requires setting of artificial ad-hoc parameters. These kinetic parameters were obtained in this work experimentally and during ELM-free time. From the simulation results, the BCs at the point of plasma sheath, and T_e=75 eV, T_i=108 eV, $V_{\|}^{i}$=$2 \cdot 10^4$ m/s, are: Mach number is 0.8, γ_e=2.1 at wall, γ_i=5.9 at wall, φ=3.04 at inner and φ=3.07 at outer divertor. The sheath parameters do not deviate drastically from the classical values. That small deviation is caused by some collision effects that affect on the sheath. In time depending simulations the sheath transmission coefficients and the Mach number are not changed. This method for calculation the BCs at the sheath, will be used for analysis of Type-I ELM in our future analysis.

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