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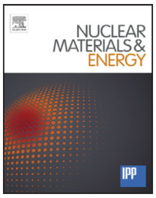

Surface roughness effects on plasma near a divertor plate and local impact angle

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ABSTRACT

The impact of rough surface topography on the electric potential and electric field is generally neglected due to the small scale of surface roughness compared to the width of the plasma sheath. However, the distributions of the electric potential and field on rough surfaces are expected to influence the characteristics of edge plasma and the local impact angle. The distributions of plasma sheath and local impact angle on rough surfaces are investigated by a two dimension-in-space and three dimension-in-velocity (2d3v) Particle-In-Cell (PIC) code. The influences of the plasma temperature andsurface morphology on the plasma sheath, local impact angle and resulting physical sputtering yield on rough surfaces are investigated.

1. Introduction

The modification of the surfaces of components exposed to the severe radiation environment in fusion devices is an important issue for the performance and lifetime of plasma facing components (PFCs) [1–6]. The repetitive processes of erosion and deposition of wall species lead to the build-up of fuel-containing mixed material layers, which has a strong implication for the operation of future reactors due to tritium retention and for being a potential source of dust and flakes in the case of disintegration of such films [7–10]. The surface topography is identified as one of the critical issues with regard to the processes of material erosion, impurity transport and redeposition in different tokamaks [11–15]. Several works have been conducted regarding the dynamics of the surface topography [16–18], the impact of surface roughness on material sputtering [19–26] and plasma characteristics [27,28] and non-uniform erosion-deposition behaviourof impurities [29]. However, the characteristics of plasma sheath on rough surfaces are considered as an uncertainty in the understanding of distributions of electric potential and field and the resulting local impact angle on rough surfaces.

The characteristics of plasma sheath have a strong influence on the energy and angle of impinging ions, which are decisive parameters for the calculation of the physical sputtering yield [30]and the reflection coefficient [31]. Therefore, the distributions of the electric potential and electric field as well as the local impact angle on rough surfaces are studied in this work by the two dimension-in-space and three dimension-in-velocity (2d3v) Particle-In-Cell(PIC) code [32]. The PIC model has the advantage of kinetic methods and the capacity of treating the complicated geometry of the simulation domain, which has been extensively used in the plasma studies. Several PIC simulations have been performed to check the potential distribution around the gap entrance between divertor tiles [33–37]. In the present study, simulations are carried out in order to elucidate the impact of surface roughness on the distributions of the sheath potential, electric field and local impact angle. Further, the effects of the plasma temperature and surface morphology on the plasma sheath, local impact angle and resulting physical sputtering yield are investigated.

2. Simulation models

The 2d3v parallel PIC code is employed to investigate the characteristics of the plasma sheath and local impact angle on rough surfaces. The deuterium ions and electrons are simulated, and the ion-electron mass ratio is 3672. The electrons obey Maxwellian distribution and the ions move with the shifted Maxwellian distribution with drifting velocity c_s (ion sound speed) at the top boundary of the simulation domain. The direction of ion drifting

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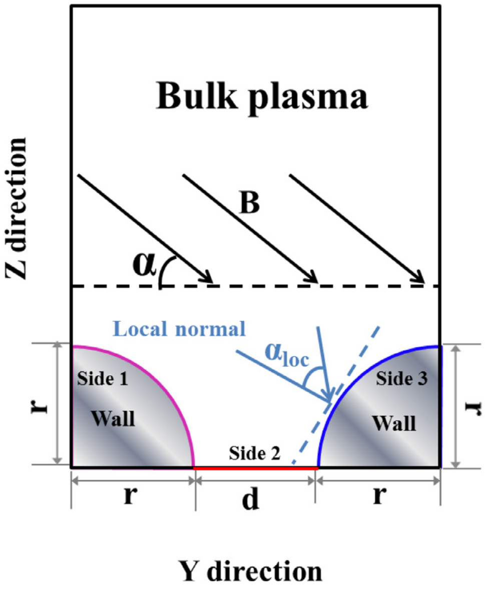

Fig. 1. Illustration of the simulation domain.

velocity is along the magnetic field direction. The total number of the mesh is 390,000 ($N_y = 30$ and $N_z = 13{,}000$) and the average number of simulated particles per cell is 145–200. The charges of deuterium ions and electrons are assigned to the grid points using the cloud-in-cell (CIC) scheme [38]. The space-dependent electric field is calculated according to the Poisson's equation while the magnetic field is fixed and prescribed. The library of SuperLU for the direct solution of large, sparse and non-symmetric systems of linear equations is used to solve the Poisson's equation [39]. The mathematical calculation of the particle trajectories of ions and electrons is treated by means of the Boris method [40].

Fig. 1 shows the simulation domain including the bulk plasma region and the rough surfaces. The simulation domain is filled with the plasma with electron and ion temperature ($T_e = T_i$, varied between 5 and 20 eV), and plasma density $n_e = 1.0 \times 10^{19}\ \mathrm{m}^{-3}$. The dimensions of the simulation domain are1.3 mm in the z direction and (d + 2r) in the y direction (surface roughness r = 1.0 µm). The non-flat surface is approximated by staircase as the shaped gap simulation [36,37]. The magnetic field lines are oblique, making an inclination angle of $\alpha = 5°$ with the smooth surface in the y direction. The space and time steps are 0.1 µm and 2.5×10^{-13} s, respectively. In the modelling, we set plasma temperature $T_e = 20$ eV, valley width d = 1.0 µm and magnetic field strength B = 2.5 T as the reference case unless stated otherwise. The bulk plasma side and the wall surface serve as the top and bottom boundaries, respectively. The top boundary is treated as a quasi-neutral plasma source (n_e=n_i). The ions and electrons are tracked until they reach the absorbing and conducting wall. The periodic boundary condition is used in the y direction in the simulation. The rough wall surface is set to the potential $V_0 = -3\ kT_e/e$ [41] while the plasma side at the top boundary is set to the potential $V_L = 0$ [33]. The local impact angle α_{loc} is calculated according to the incident direction of the ions and the local surface normal of rough surface at the impact position.

3. Results and discussion

The distribution of the potential in the simulation domain and the sheath electric field near the target surface for the reference case is illustrated in Fig. 2. According to the result in Fig. 2, the spatial resolution (0.1 µm) is high enough to perceive the variation of the electric field in space. Fig. 3(a) shows the profiles of the plasma density and potential in space. The modelled potential profile is used by Boltzmann distribution $n_e(z) = n_0 \exp(e\varphi/kT_e)$ to check the relationship between the potential and density profiles in Fig. 3(a). The resulting electron density distribution calculated by the Boltzmann distribution is in good agreement with the PIC-simulated electron density distribution, as shown in Fig. 3(b). In the following analyses, the sensitivity studies are performed to assess how strongly the plasma sheath and local impact angle depend on the plasma temperature,surface morphology and magnetic field due to the kinetic characteristic of background plasma.

3.1. The influence of the plasma temperature

The investigation of the local impact angle distributions on rough surfaces for different plasma temperatures is presented in Fig. 4(a). The local impact angle distributions of plasma ions D^+ for different plasma temperature are almost the same, as shown in Fig. 4(a) and Table 1. The 1D PIC code in the ref [42] has given the same temperature effect on the local impact angle distributions. In addition, the local impact angle distribution on smooth surface for the reference case is also shown in Fig. 4(a), which shows obvious difference from the rough surface. The local impact angle distribution on the rough surface but with the electric field from the smooth surface which is uniform in the y direction is also shown in Fig. 4(a). It can be seen that there is a little difference between the smooth surface case and the rough surface case. When the roughness amplitude increases, the electric field near the rough surface would have a stronger impact on the plasma trajectory, and

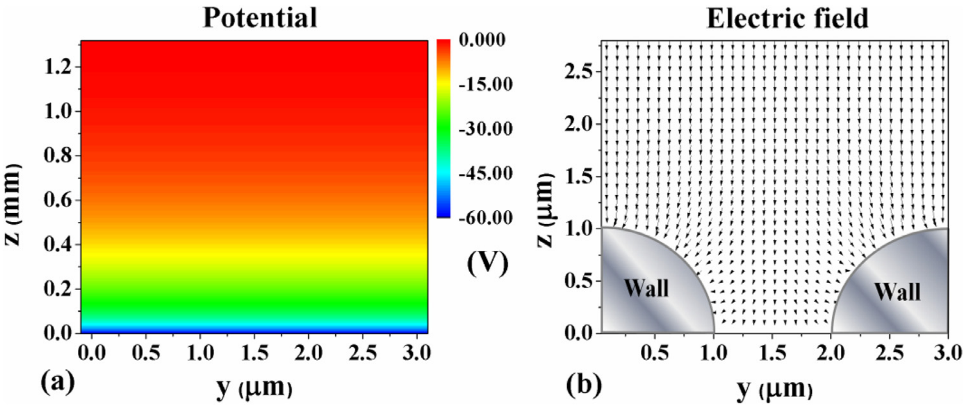

Fig. 2. The distribution of (a) the potential in the simulation domain and (b) the electric field near the target surface for the reference case. The arrows indicate the directions of the electric field in space.

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