ARTICLE IN PRESS
JID: NME [m5G;January 27, 2017;18:54]
Nuclear Materials and Energy 000 (2017) 1–5
Contents lists available at ScienceDirect
Nuclear Materials and Energy
journal homepage: www.elsevier.com/locate/nme

A Particle-In-Cell approach to particle flux shaping with a surface mask

G. Kawamura [a,b,*], N. Ohno [c], S. Takamura [d], Y. Tomita [e]

[a] National Institute for Fusion Science, National Institutes of Natural Sciences, 322-6 Oroshi-cho, Toki 509–5292, Japan
[b] Department of Fusion Science, SOKENDAI, 322-6 Oroshi-cho, Toki 509–5292, Japan
[c] Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464–8603, Japan
[d] Faculty of Engineering, Aichi Institute of Technology, Yakusa-cho, Toyota 470-0392, Japan
[e] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui 230031, China

ARTICLE INFO

Article history:
Received 15 July 2016
Revised 8 November 2016
Accepted 8 December 2016
Available online xxx

2010 MSC:
82D10
78A35

Keywords:
Sheath
Flux distribution
Particle-In-Cell
Simulation

ABSTRACT

The Particle-In-Cell simulation code PICS has been developed to study plasma in front of a surface with two types of masks, step-type and roof-type. Parameter scans with regard to magnetic field angle, electron density, and mask height were carried out to understand their influence on ion particle flux distribution on a surface. A roof-type mask with a small mask height yields short decay length in the flux distribution which is consistent with that estimated experimentally. A roof-type mask with a large height yields very long decay length and the flux value does not depend on a mask height or an electron density, but rather on a mask length and a biasing voltage of the surface. Mask height also changes the flux distribution apart from the mask because of the shading effect of the mask. Electron density changes the distribution near the mask edge according to the Debye length. Dependence of distribution on parameters are complicated especially for a roof-type mask, and simulation study with various parameters are useful to understand the physical reasons of dependence and also is useful as a tool for experiment studies.

1. Introduction

Estimation and control of damage to plasma facing components is one of the critical issues to realize a fusion device within an acceptable construction cost. In addition to in situ experiments in large experiment devices [1], exposure experiments in linear devices are widely performed [2,3] to utilize long exposure time and well-controlled plasma conditions. An experimental application of a surface mask to control a particle flux distribution along a base surface was reported recently [3]. It was demonstrated that a partial mask over a metal surface realizes a spatially varying distribution of ion particle flux during a steady-state discharge in NAGDIS-II device [4].

Particle flux is usually measured by a Langmuir probe and its distribution can be measured by a probe array [5]. The spatial scale of distribution observed under a mask is typically 10 to 100 μm [3]. It is difficult to measure a micro-scale distribution because a probe disturbs the plasma, and there is no space to install a probe under the mask. However, estimation of a flux distribution is essential for a reliable analysis of experimental results. For this purpose, we employed a Particle-In-Cell (PIC) simulation. A PIC simulation can be a powerful tool to estimate a flux distribution and to know its dependence on physical parameters. Two dimensional PIC simulation codes such as SPICE2 [6,7], EPPIC2D [8,9], and EDDY [10,11] have been employed for analysis of particle and heat flux on surfaces of castellated tiles in ITER and existing tokamak devices. We have developed an electrostatic PIC code for Sheath plasma, PICS. There are the 1D version, PICS1, and the 2D version, PICS2. The 2D code has flexibility of a surface geometry.

In this paper, a PIC simulation study is presented to investigate distribution of the flux with two types of mask: 1) a thick mask on a surface and 2) a thin mask over a surface. We call them a step-type mask and a roof-type mask, respectively. Estimation of the flux distribution and a sensitivity study are the objectives of this work. In Section 2, simulation model and technical information of the codes are described. In Sections. 3.1–3.4, examples of simulation with the two types of masks, influence of misalignment, electron density, and height of a mask are discussed, respectively. In Section 4, results are summarized.

* Corresponding author.
E-mail address: kawamura.gakushi@nifs.ac.jp (G. Kawamura).

http://dx.doi.org/10.1016/j.nme.2016.12.017

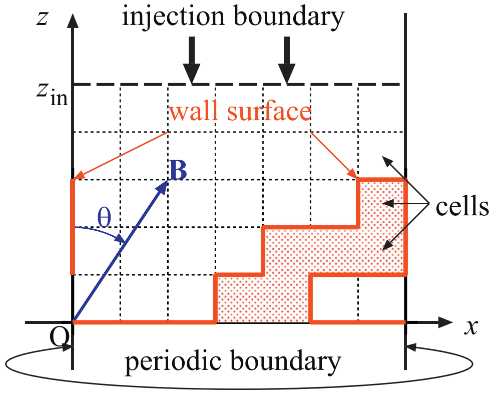

Fig. 1. Boundary conditions and an example of surface geometry of the simulation box of the PICS2 code. The code has injection boundary of plasma at $z = z_{\rm in}$ and two periodic boundaries in x-direction. The cells used for calculation of potential are drawn as dotted lines.

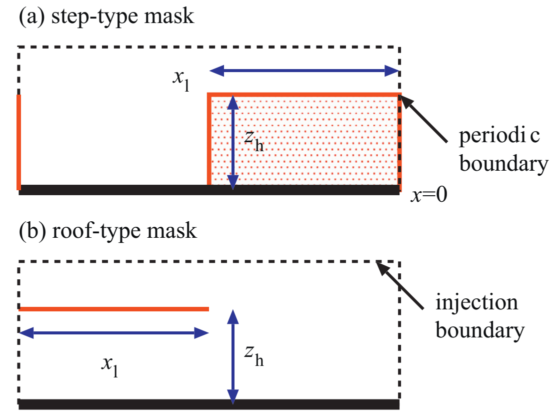

Fig. 2. Two types of masks: (a) step-type and (b) roof-type. The red lines on the left boundary and the right boundary are the same mask surface because of the periodic condition. The length and the height of the mask are denoted by $x_{\rm l}$ and $z_{\rm h}$, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Particle-In-Cell modeling of a sheath plasma

We employed the electrostatic two-dimensional PIC code PICS2 to model a Debye sheath and a magnetic presheath in front of a plasma facing wall. Fig. 1 shows a simulation box used by the codes. A spatially uniform and temporally constant magnetic field is applied with direction defined by the angle θ from the z-axis. The PICS2 code uses 2d3v PIC models and has an injection boundary of plasma at $z = z_{\rm in}$ and an absorption boundary at $z = 0$. The simulation region is divided into cells in a Cartesian coordinate system. PICS2 has an additional absorption boundary to model a plasma facing wall consisting of line segments such as the example in Fig. 1. Each segment is placed on the cell boundary. Although a curved line is not strictly realized, an arbitrary shape can be approximately implemented as a sequence of vertical and horizontal segments if the spatial resolution is shorter than the characteristic length of the plasma, i.e., the Debye length. PICS2 has two periodic boundaries in the x-direction. The potential on the wall is spatially uniform and the value is determined to realize electrically floating or biasing conditions.

Velocity distributions of injected electrons and ions are assumed to be Maxwellian with velocity cutoff due to electron loss at the wall and a drifting Maxwellian to the direction of the magnetic field, respectively. The drifting speed is ion sound speed resulting from the acceleration in a collisional presheath in front of a magnetic presheath. The velocity distributions as functions of parallel and perpendicular velocities are given by the following equations excluding their normalization factors:

$$f_{\rm e}(v_\parallel, v_\perp) \propto \exp\left(-\frac{v_\parallel^2}{2v_{\rm te}^2} - \frac{v_\perp^2}{v_{\rm te}^2}\right), \quad (1)$$

$$f_{\rm i}(v_\parallel, v_\perp) \propto \exp\left(-\frac{(v_\parallel + v_{\rm d})^2}{2v_{\rm ti}^2} - \frac{v_\perp^2}{v_{\rm ti}^2}\right). \quad (2)$$

Thermal speeds, drifting speed, electron and ion masses, temperatures, and ratio of specific heat are denoted by $v_{\rm te} = \sqrt{T_{\rm e}/m_{\rm e}}$, $v_{\rm ti} = \sqrt{T_{\rm i}/m_{\rm i}}$, $v_{\rm d} = \sqrt{(T_{\rm e} + \gamma T_{\rm i})/m_{\rm i}}$, $m_{\rm e}$, $m_{\rm i}$, $T_{\rm e}$, $T_{\rm i}$, and $\gamma = 3$, respectively. We note that the drifting velocity must have a negative component along the z-direction because particles are injected from $z = z_{\rm in} > 0$.

New particles are generated in front of the injection boundary with a certain margin, $z_{\rm m} > 0$, to avoid influence of the electric field of the Debye sheath and the magnetic presheath on the bulk plasma at $z < z_{\rm in}$. The initial position of each particle is determined from the guiding-center at $z = z_{\rm in} + z_{\rm m}$. The margin involves empirical factors, and we use $z_{\rm m} = 3v_{\rm i}\Delta t|\cos\theta| + 3\rho_{\rm ti}|\sin\theta|$. Time step of simulation, mean ion gyration radius, charge of ion, magnetic flux density are denoted by Δt, $\rho_{\rm ti} = q_{\rm i}B/m_{\rm i}$, $q_{\rm i}$, and B, respectively. We note that the simulation box must be sufficiently long in the z-direction to have negligibly small electric field at the injection boundary. We used $z_{\rm in} = 10\lambda_{\rm De} + 10\rho_{\rm ti}|\sin\theta|$. The factor of each term is empirical and an adjustment might be necessary according to plasma parameters and the magnetic field. The Debye length, the permittivity of free space, the elementary charge, electron density at the injection boundary are denoted by $\lambda_{\rm De} = \sqrt{\epsilon_0 T_{\rm e}/e^2 n_0}$, ϵ_0, e, and n_0, respectively. Particles with larger z-position than $z_{\rm in}$ move according to the equation of motion without electric field but their contribution to the space charge is discarded. Particles with their guiding centers at $z > z_{\rm in} + z_{\rm m}$ are removed in each time step.

Although the characteristic length of a magnetic presheath depends on magnetic flux density and temperature, it is typically of the order of mm or cm in the case of fusion plasmas and their related laboratory plasmas. Ionization, charge exchange, and other collisional processes are not included in the codes because their mean-free-paths are typically longer than the simulation box. The codes are capable of secondary electron emission determined by an emission coefficient although it is not used because a large negative biasing voltage is assumed. The codes are written in fortran 90 and parallelized with OpenMP. The codes do not depend on numerical libraries and will run on most types of computers including a Windows PC, a Macintosh and a Linux workstation.

3. Simulation results and discussions

3.1. Geometry and parameters used in simulation

We simulate two types of surface mask: a step-type mask and a roof-type mask illustrated in Fig. 2. A roof-type mask uses a thin foil above the base surface at $z = 0$. Both of them are expected to cause a gradient of particle flux on the base surface. A step-type mask has an advantage in ease of assembly and a roof-type mask has an advantage in a wide range of flux under the mask. The experiment of helium-plasma exposure on a tungsten plate used a roof-type mask because wide range of flux was preferable [3]. We parameterized the mask with vertical height, $z_{\rm h}$, and horizontal length, $x_{\rm l}$, where particles are absorbed. We assumed metallic masks which have the same electrostatic potential on the surface. In the experiment, a tungsten foil is employed as a mask in Ref. [3]. We employ the following parameters of He^+ plasma as a refer-