A study of magnetized plasma sheath near solids of different geometries

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Abstract

Results of two-dimensional PIC particle simulations are presented. We investigated electropositive (EP) low-temperature Ar plasma as well as idealized electronegative plasma with variable electronegativity (EN). The EN plasma contained electrons, Ar^+ and O^- ions and a continuous negative background of Ar. Our aim was first to describe an electropositive magnetized sheath and then to study the effects of EN species (i.e. heavy negative charge carriers) on the structure of sheath and on the transport of particles. This complex problem is very complicated to describe analytically using currently available theories - especially in the case of collisional plasma. But the understanding of these processes is very useful not only for many material treatment applications using magnetrons, but also for analyses of plasma probe diagnostics and analyses of edge plasma in tokamaks.

Introduction

In this contribution we analysed the sheath region in the vicinity of cylindrical Langmuir probe and a planar substrate with a groove. The probe was immersed into a magnetized low-temperature plasma with variable amount of heavy negative charge carriers, i.e. electronegative compound of plasma. Our method of study was computer simulation – a particle-in-cell model with Monte Carlo-based simulation of collisions (PIC-MCC model). This approach is, unlike the continuous models, relatively easy-to-write and gives precise results also on a microscopic scale. The main disadvantage lies in its demand on a computational time. A good compromise in terms of computational time and detail of results seems to be achieved by "hybrid models" which combine continuous and particle codes in iterative, spatial or energy manner [1]. Unfortunately, this approach is limited by some approximations which often concern a minimal pressure of the plasma to be able to use drift-related equations. The second part of our results was verified by such hybrid simulation which was developed in our department too.

The problem of a Langmuir probe in magnetized plasma is still an object of analytical studies. As mentioned in [2], the degree of influence of the magnetic field on the probe currents is given by the parameter $\beta = r_p/r_L$, i.e. by the ratio of probe radius and Larmor radius of collected species. Higher β means that the I-V characteristics, or at least parts of it, cannot be interpreted in a traditional way. The diffusion perpendicular to magnetic field lines is defined as $D_\perp = D/(1+\omega^2\tau^2)$ [3]. Therefore, the degree of anisotropy is also given by the ratio of λ and r_L.

The analytical description gets more complicated for collisional plasma, non-trivial geometries or electronegative plasma. However, the understanding of the processes under these conditions is needed for many technological applications such as magnetron sputtering or e.g. for Langmuir probe analysis of edge plasma in tokamaks.

Description of simulation

The plasma simulated in this paper is an "idealized electronegative plasma" containing electrons, positive and negative ions and continuous neutral background used for collisions of charged particles. The density of charged particles in undisturbed plasma is $n_+ = n_e + n_- = 1 \times 10^{15}\,\mathrm{m}^{-3}$ and the electronegativity is a variable parameter $\varepsilon = n_-/(n_- + n_e)$. The pressure was set to 1 Torr (133 Pa) and probe bias with respect to space potential was set to +10 V. In our simulation the positive ions are represented by Ar^+ ions, negative ions by O^- and neutral background by Ar atoms. The computational domain is square-shaped with a) probe located in the centre or b) planar substrate with a groove. The main parameters are shown in figure 1.

	e	Ar^+	O^-
λ [mm]	0.70	0.04	0.07
r_L[mm]	0.06	1.80	1.10
$\langle E\rangle$[eV]	3.00	0.04	0.04

domain size	3 × 3 cm
probe radius	0.1 mm

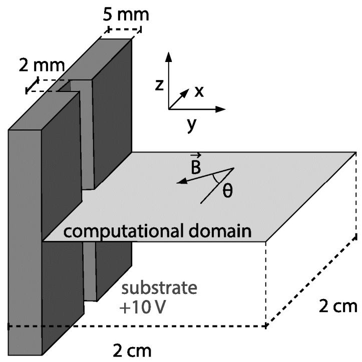

Figure 1. Parameters of the plasma. Left top: common parameters $- r_L$ is estimated mean value of Larmor radius $m\langle v\rangle/(|q|B)$ valid for $B = 0.1$ T. Left bottom: configuration a) with Langmuir probe. Right: configuration b) with grooved substrate.

Langmuir probe in magnetic field

We obtained interesting results even for the case of $\varepsilon = 0$, i.e. in electropositive plasma. Figure 2 in the middle shows electron density near the probe along magnetic field lines (y = 0) and perpendicularly (x = 0). The non-magnetic solution was described previously e.g. in [4]. However, when a sufficiently strong magnetic field was applied, the local maximum of n_e increased in the perpendicular direction to $\vec{B}$ and disappeared along $\vec{B}$. This effect is caused by simultaneous influence of magnetic and electrostatic fields which formed, in fact, two "electron traps" near the probe on line x = 0. Lower electron density along $\vec{B}$ can be explained by fast electron absorption by the probe along $\vec{B}$ which could not be fully balanced by electron diffusion from distant regions. The gradual change from non-magnetic maximum to "trap" maximum is shown in figure 2 on the right.

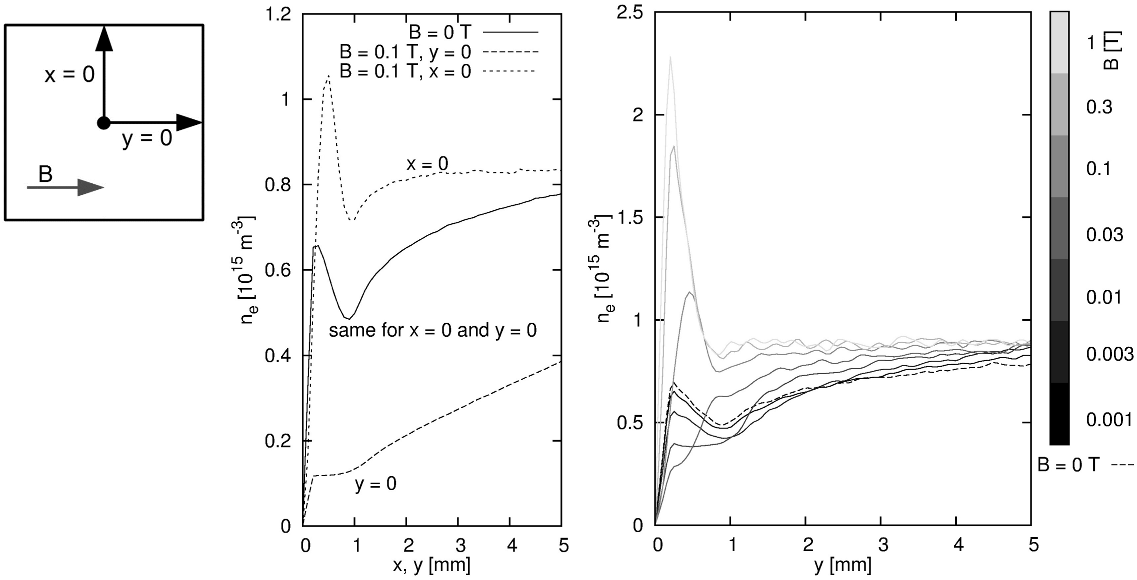

Figure 2. Electron density near the probe in electropositive magnetized plasma.

The addition of heavy negative charge carriers changed the situation. Ions, being less influenced by $\vec{B}$, were able to partially replace electrons in the region where there was a lack of electrons due to insufficient diffusion. The ion density is compared to the electron density in figure 3 in the middle which shows the situation outside the sheath, 5 mm from the probe. Figure 3 on the right shows polar plot of O$^-$ flux to the probe where the preferential direction of impact along $\vec{B}$ is obvious for all values of electronegativity. We also observed decrease of sheath deformation with increasing electronegativity.

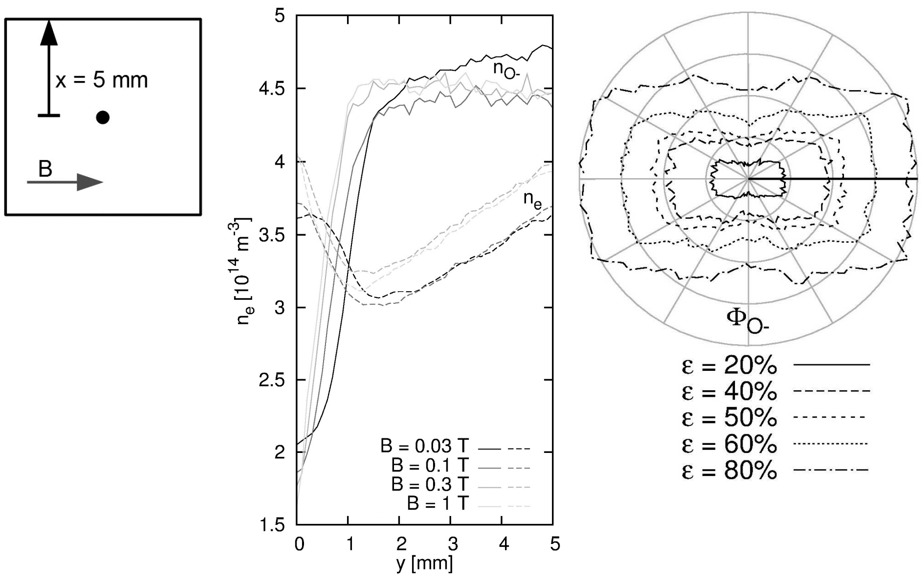

Figure 3. Middle: Comparison of electron and O$^-$ density outside the sheath at $\varepsilon = 50\%$. Left: polar flux of O$^-$ to the probe for different ε at $B = 0.1$ T.

Grooved substrate in magnetic field

The situation got different in the case of planar substrate. The absorption of electrons whose movement is bound with the magnetic field, take place from the whole computational area. We cannot find any magnetic field line that do not cross the substrate and where the electron density would be, therefore, higher. The flux of electrons to the substrate is governed only by magnetic field and the results are as expected. Figure 4 shows electron fluxes along the groove edge. Non-magnetic solution was already published in [5]. The maximum of fluxes was found on the outer corners of groove while the minimum of fluxes is on inner corners. The magnetic field oriented towards the substrate ($\theta = \pi/2$ - see fig. 1 on the right) was able to lead electrons down to the bottom of the substrate. On the other hand, for the orientation $\theta = \pi/4$ we could observe higher flux of electrons on one of the sides of the groove. The fig. 4 shows also the comparison with the hybrid model which is satisfactory even in absolute values which were not fitted.

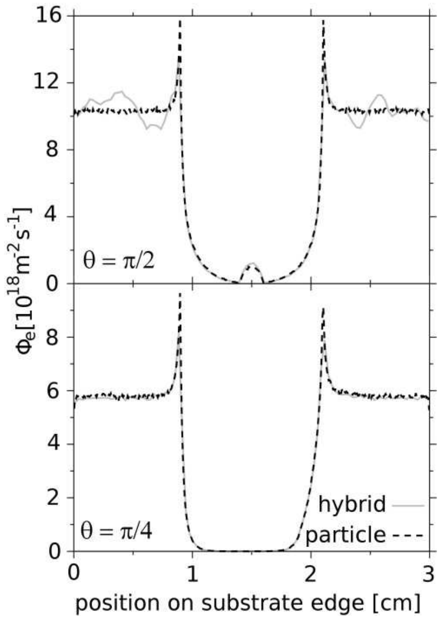

Figure 4. Fluxes of electrons to the grooved substrate for different orientation of $\vec{B}$

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References

[1] V. Hruby, R. Hrach and Z. Pekarek, Vacuum **86** (2012), 1228-1231.

[2] R. Hippler, S. Pfau, M. Schmidt and K. H. Schoenbach, Low temperature plasma physics – fundamental aspects and applications, Wiley-VCH, Berlin, 2001.

[3] R. H. Huddlestone and S. L. Leonard, Plasma diagnostic techniques, Academic Press, New York, 1965.

[4] E. Havlickova, P. Bartos and R. Hrach, J. Phys.: Conf. Ser. **63** (2007), 012019.

[5] T. Ibehej and R. Hrach, Vacuum **86** (2012), 1220-1222.