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2D PARTICLE-IN-CELL SIMULATION OF DC MAGNETIZED PLASMA IN CYLINDRICAL CONFIGURATION[1]

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We report on 2D Particle-In-Cell (PIC) simulations of dc magnetized plasma in cylindrical coordinates. Simulations aremade by XOOPIC code developed on the University of California, Berkeley. Results of the simulation are compared with experimental data obtained by Langmuir probe and emissive probe diagnostics in cylindrical magnetron device.

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1 Introduction

PIC method of plasma simulation is widely used in plasma physics research because of its reasonable results and ability to solve wide range of problems in its kinetic approach. Regarding to description of PIC method we refer to [1]. We present here 2D PIC simulations of magnetized dc discharge in cylindrical magnetron device. Magnetrons are used in industry e.g. for thin film layer coating and etching. Many magnetron configurations are used. In our research we concern on discharge in the cylindrical magnetron device because its symmetry and simple magnetic field arrangement enables relatively simple theoretical description and makes easier understanding of processes in weakly magnetized plasma avoiding effects of nonhomogenous magnetic field. We study the influence of the magnetic field on discharge parameters and PIC model of discharge can contribute to our description.

2 Experimental system

Scheme of the cylindrical magnetron device used for experimental research in our laboratory is depicted in Fig. 1 and is described in detail in [2] so that only its overview will be given at this place: Cylindrical magnetron consists of grounded stainless steel tube (anode) and water cooled cathode at its axis. Discharge area (12 cm long) is constrained by two metallic limiters connected

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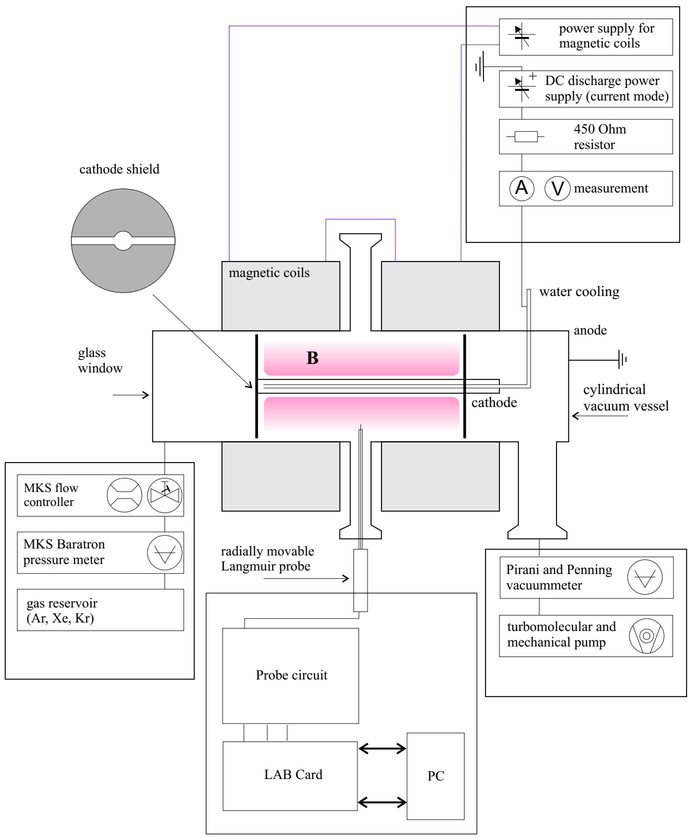

Fig. 1. Cylindrical magnetron scheme. Faculty of Mathematics and Physics, Charles University in Prague.

to the cathode potential. Plasma in magnetron is confined by homogenous magnetic field parallel to axis. It is created by couple of magnetic coils and can vary up to $40\ \mathrm{mT}$. Magnetron usually operates in noble gases at pressures $1\ -10\ \mathrm{Pa}$. Plasma parameters can be determined by means of electrical probes placed in vacuum feedthrough in the central plane of magnetron. Some experimental data presented in this contribution are obtained in similar cylindrical magnetron (see e.g. [3]) that differs from that one described here in length of discharge area ($30\ \mathrm{cm}$ instead of $12\ \mathrm{cm}$) and also in electrodes radii (anode radius is $28\ \mathrm{mm}$ and cathode radius is $9\ \mathrm{mm}$). Let us to denote these two magnetrons like ”longer” and ”shorter” magnetron for easier handling in this text. Shorter magnetron’s dimensions are given in Fig. 2 .

3 2D PIC model of the magnetron

For simulations we applied XOOPIC code [4] developed on the University of California, Berkeley. Scheme of region for our 2D PIC model of discharge in cylindrical magnetron is depicted

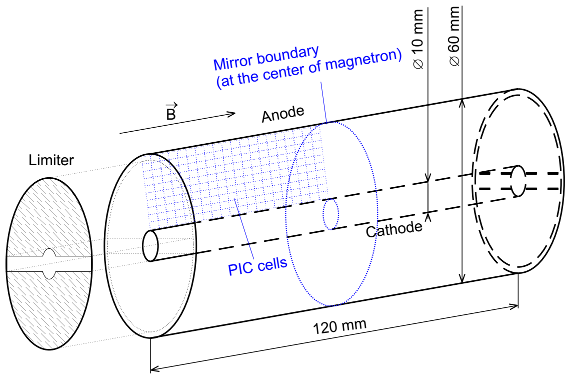

Fig. 2. : Scheme of region for 2D PIC simulation of discharge in the "shorter" magnetron.

in Fig. 2. 2D code is suitable for this problem because of symmetry of magnetron arrangement. Symmetry could enable in principle even 1D description, but we know from experiment, that discharge is not homogenously distributed along the whole discharge region. In order to reduce computational effort we placed reflecting boundary to the middle of magnetron and we simulated only half of discharge area (from the center to the left limiter). However, simulation remained still relatively time consuming. This is because conditions had to be fulfilled that ensure stable and physically correct solution. According to [5] it means: 1.) cell length smaller or comparable with Debye length (that is in the order of tens of $\mu\mathrm{m}$ in magnetron), 2.) reasonable number of simulating superparticles in cell (optimally 10 to 50 per cell – this was not fulfilled in our simulation because of too high computational requirements) and 3.) time step restrictions: time step must resolve processes on plasma frequency and particles need not fly over more than one cell in one time step.

4 Results of model and comparison with experiment

An example of computational results is presented in figure 3. It is obtained in simulation where cells dimensions were comparable with Debye length. Comparison of computational electron density results with Langmiur probe data is given in Fig. 4 for two different experimental conditions; r_A denotes anode radius. Considering that maximum of the electron density is proportional to the applied power we can see satisfactory agreement of model results with experimental data. Maximum of computed electron density is situated approximately at the same position like in experiment. Profile of the electron density in the region of positive column corresponds better to Langmuir probe data obtained at higher magnetic field ($25\ \mathrm{mT}$, $5\ \mathrm{Pa}$ – note the ratio of the magnetic induction over pressure remains the same: $B/p = 5\ \mathrm{mT/Pa}$).

An important criterion of physical reliability of our computational results is plasma potential profile (Fig. 3b). The discrepancy in the plasma potential profile in our former 1D model of magnetron [6] was the motivation to apply 2D model. In 1D model dropped more than one half of applied discharge voltage in the anode regions and in the positive column (positive column was not in fact developed at all). This is in contrast with data obtained in discharge by Langmuir

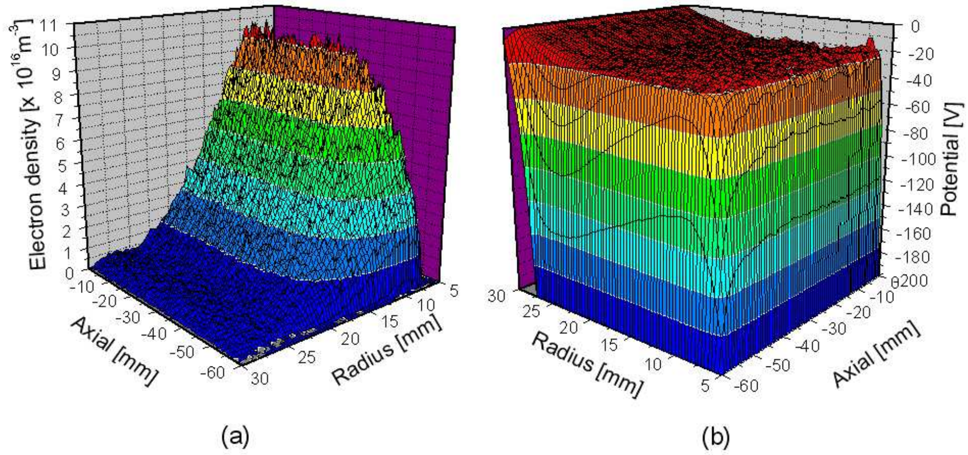

Fig. 3. XOOPIC simulation results of Argon discharge in magnetron at $p = 4\,\mathrm{Pa}$, $B = 20\,\mathrm{mT}$, $U_{Cathode} = -200$ V. Data are from snapshot taken at discharge time $t = 6,4 \times 10^{-7}$ s. Density profile used for initial condition was obtained from former simulation with rougher computational grid. Zero of axial coordinate denotes center of magnetron; $r_{Anode} = 30$ mm; $r_{Cathode} = 5$ mm. Cell dimension is comparable with Debye length (i.e. 500×1250 cells). (a) electron density profile, (b) potential profile (for better view 90° clockwise rotated).

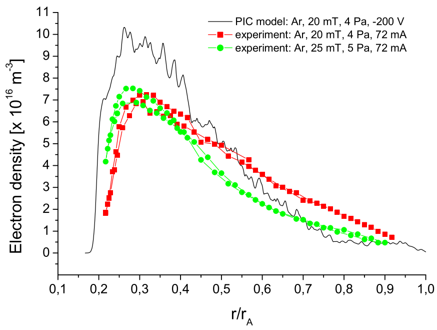

Fig. 4. Comparison of computed radial density profile with data measured by Langmuir probe. r_A is anode diameter.

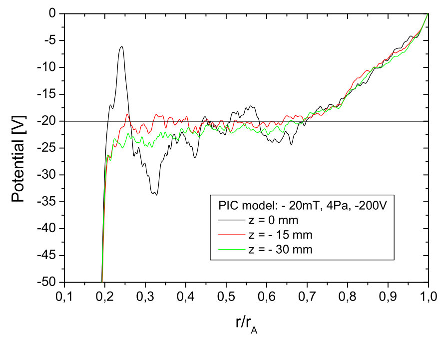

Fig. 5. Detail of computational potential profile at three different axial positions. r_A is anode diameter, $z = 0$ denotes the center of the magnetron.

probe diagnostics. These experimental data showed only small potential fall in anode regions as well as in positive column. Almost the whole applied voltage was spent in cathode regions.

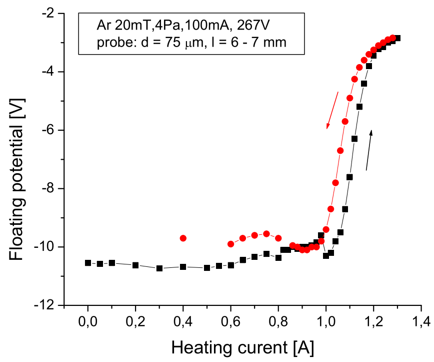

Fig. 6. Heating characteristics of emissive probe. Operating point determined at 1.3 A.

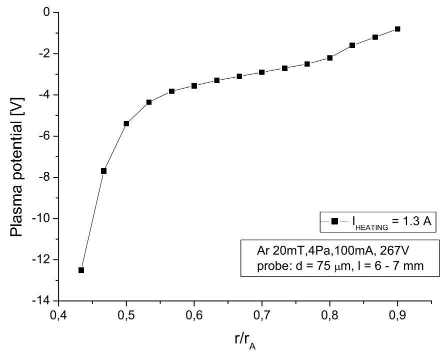

Fig. 7. Radial profile of plasma potential obtained by strongly emitting probe in ”longer” magnetron.

Despite that, electron density profile obtained in 1D model corresponded relatively well with the experiment.

In our former 2D simulations with rougher computational grid presented e.g. in [7] we obtained potential profile that corresponded better with Langmuir probe results than in case of 1D model. Region of positive column is relatively broad and is well developed. But the potential fall in anode regions was almost 40 V (from 200 V of applied voltage) and furthermore number of simulating particles monotonously grew during computation - computation was not stable. The presented simulation was already stable and was made with gird cell size comparable in both directions with Debye length. Resulting plasma potential profile (Fig. 3b) is in detail depicted at three different axial positions in 5. We can see flat and well developed positive column like in simulation [7], but potential profile is better resolved and potential fall in anode regions is smaller.

To compare of potential profile with experiment we used plasma potentials obtained from the zero cross of the second derivative of the Langmuir probe characteristic. In order to validate experimental plasma potential profile by another method we measured plasma potential profile in magnetron by emissive probe too (in fact the potential shifted by kT_e/e is measured [8]). These measurements have been realized in the ”longer” magnetron. Emissive probe data are depicted in Fig. 6 and Fig. 7. From data in Fig. 6 we determined sufficient value of heating current at which the floating potential of the emissive probe was already good approximation of plasma potential (1.3 A at given experimental conditions). Emissive probe data (see Fig. 7) confirmed results obtained by Langmuir probe: potential fall in the region of the positive column was only a few volts as well as the potential fall in the anode regions.

Big potential fall in anode regions in the simulation can be caused by some of these factors: a) grid is not still fine enough, b) discrepancy is observed because of the noise in potential caused by small number of superparticles per one cell, c) model doesn’t involve all processes participating in burning discharge. Solution of this discrepancy will be object of our future work.

5 Conclusion

We used 2D PIC code for modeling of weakly magnetized dc discharge in the cylindrical magnetron. In our recent simulation with grid comparable with Debye length we obtained stable solution that is in relatively good consistency with experimental results. Despite that qualitative agreement of simulation results with experiment was found, further improvement of model is needed because of relatively big potential fall was observed in anode regions in simulation in comparison to data obtained by emissive as well as Langmuir probe measurements.

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