Particle-based simulations of rotating spokes in radio frequency magnetron discharges

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Magnetron sputtering represents an advanced technique widely used in the industrial material processing, particularly, the high-quality thin films manufacturing. Azimuthal spokes is a ubiquitous oscillation mode in magnetron discharge plasmas, as well as in other typical **E×B** plasma sources, such as Hall thrusters and Penning discharges. The spoke mode significantly affects the dynamics of electrons and ions and its fundamental understanding is hereby of significant importance in the operation and control of magnetron sputtering discharges. Although spokes in direct current and pulsed magnetrons were studied extensively, their presence and the underlying physics are little studied in radio frequency (RF) driven magnetron discharge, which is an important technique for the deposition of both insulating and conducting films. The first experimental evidence of the rotating spoke in RF magnetron discharges was recently reported, but its formation and physics is not elucidated by far. In this work, the rotating spoke mode experimentally observed in RF magnetron discharges was successfully reproduced by means of 2D axial-azimuthal fully kinetic Particle-in-cell/Monto Carlo collision approach. The spoke rotates in the -**E**×**B** direction with the velocity 5 km/s, consistent with the experimental observation. The underlying physics of prominent spoke features in RF magnetron discharge: the potential hump and the RF-modulated ionization, were observed and elucidated to uncover the driving mechanism behind the spoke formation. [1, 2] The analysis of the computational results, aided by the perturbation two-fluid theory, reveals that the cathode sheath electric field $\mathbf{E}_z$ triggers the gradient drift instability (GDI), which is saturated with the destruction of the GDI condition due to the deformation of the potential and the redistribution of the electron density. As a consequence, the potential hump region forms with the presence of the azimuthal electric field $\mathbf{E}_y$. We found that in the linear stage, the instability mode wavelength and the corresponding growth rate are in good agreement with the prediction of the GDI linear theory. It is further shown that the saturation level of $\mathbf{E}_y$ is synchronized with and proportional to the cathode voltage, leading to the RF-modulation of the spoke ionization. Due to the gradient B drift induced electron energy gain is proportional to the saturation level of $\mathbf{E}_y$, it is suggested that the spoke ionization may be manipulated by the cathode voltage in DC or pulsed magnetron discharges.

References

[1] L. Xu, D. Eremin, and R. Brinkmann *Plasma Sources Science and Technology* 30, 075013 (2021).

[2] L. Xu, H. M. Sun, D. Eremin, S. Ganta, I. Kaganovich, K. Bera, and S. Rauf *arXiv*:2305.15941 (2023)

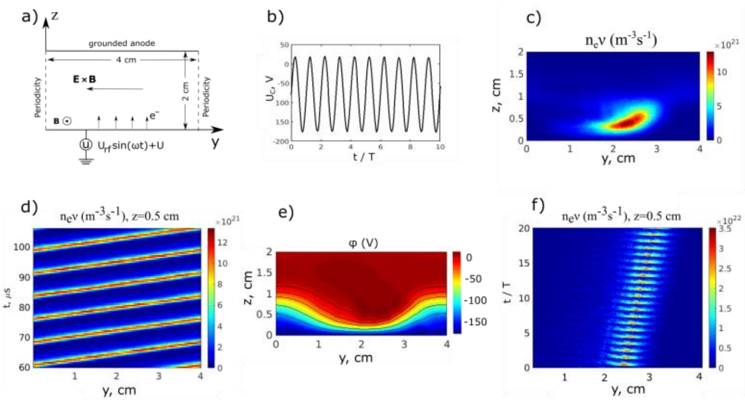

Figure a) The layout of the 2D axial (z)-azimuthal (y) PIC/MCC model of the RF magnetron plasma. b) The voltage waveform applied at the cathode. c) The 2D map of the RF period averaged ionization rate. d) The spatio (azimuthal)-temporal plot of the ionization rate in the long duration at z=0.5 cm (note the ionization rate is RF period averaged). e) The contour 2D map of potential in the steady state when cathode voltage is minimum (U=-180 V). f) The spatio (azimuthal)-temporal plot of the ionization rate in the duration of 20 RF periods at z=0.5 cm (here the ionization rate is transient instead of the RF period-averaged).