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Observation of Three-dimensional Helical-rotating Plasma Structures in Beam-generated Partially Magnetized Plasmas

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Electron beam-generated plasmas consisting of magnetized electrons and unmagnetized ions have been widely utilized in material functionalization and laboratory devices such as Penning discharges and linear plasma machines [1,2]. In these systems, beam electrons from a cathode or plasma source are injected into a grounded chamber along a uniform longitudinal magnetic field, ionizing neutral gas and producing plasmas for materials processing.

A common feature of beam-generated plasmas is the emergence of large-scale azimuthally rotating density structures, known as "spokes". These structures significantly enhance the cross-field transport of particles and energy which can potentially cause unexpected material surface damage. Understanding the formation of azimuthal structures is therefore crucial for controlling beam-generated partially magnetized plasma behavior.

In this work, we present 3D3V particle-in-cell/Monte Carlo collision (PIC/MCC) simulations of azimuthal structures in beam-generated partially magnetized plasmas using the LTP-PIC code, an extensively benchmarked explicit electrostatic PIC/MCC code on a hybrid CPU-GPU architecture [3]. The simulation domain is a grounded, fully absorbing Cartesian box filled with helium gas and subjected to a uniform longitudinal magnetic field of B=100 G (see Fig. 1). An electron beam is launched from the center of the left boundary and propagates along the magnetic field. Electron-neutral collisions (elastic scattering, excitation, ionization) and ion-neutral charge exchange collisions are included.

We identify two distinct instability regimes. At higher pressure, the quasi-neutral condition is attained [Fig. 1(g)] and a lower-hybrid instability is destabilized by the radial density gradient, equilibrium $\boldsymbol{E}\times\boldsymbol{B}$ drift and collisions, generate 2D spiral structures that enhance cross-field transport [Figs. 1(a)~1(c)]. When the gas pressure is lower than a certain threshold, quasi-neutrality is not achieved [Fig. 1(h)]. A diocotron instability arises from velocity shear and creates azimuthal vortices that disrupt the beam, leading to the formation of a 3D helical-rotating plasma structure [Figs. 1(d)~1(f)]. The axial projection of this helical-rotating structure shows behavior similar to that of the spoke, which may lead to misinterpretation of this structure in experiments. Analytical formulas are proposed for the threshold pressure between the two regimes and for the rotation frequency of the helical structure. Preliminary experimental verifications are also discussed.

References

[1] F. Zhao, Y. Raitses, X. F. Yang, A. Tan, and C. G. Tully, Carbon **177**, 244 (2021)
[2] N. Claire, A. Escarguel, C. Rebont, F. Doveil, Phys. Plasmas **25**, 061203 (2018).
[3] A. T. Powis, Particle Methods for Modeling Magnetospheric Diagnostics and Low-Temperature Plasma Physics, Ph.D. thesis, Princeton University (2018).

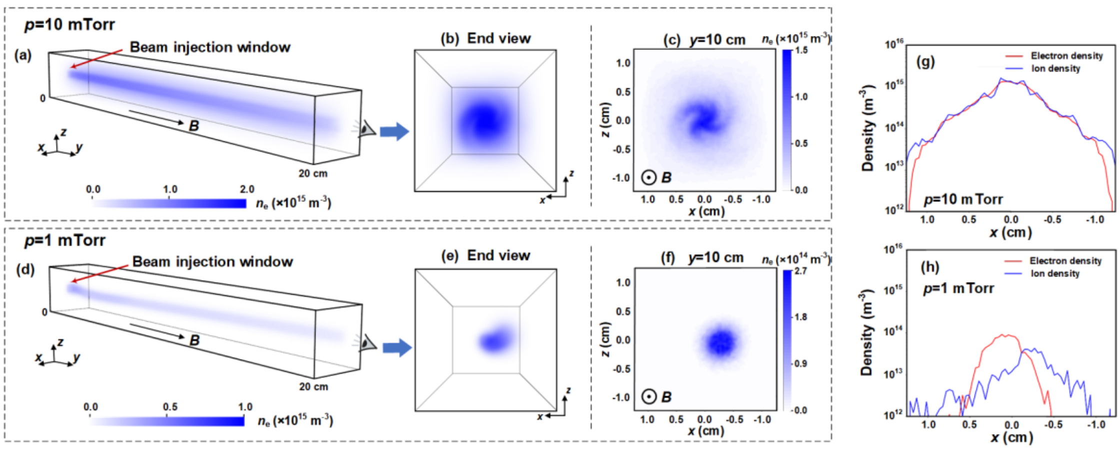

Figure 1. Electron number density profiles at quasi-steady state for p=10 mTorr (a~c) and p=1 mTorr (d~f). Subfigures (a) and (d) show the 3D distribution of electron number density, with the magnitude indicated by shaded blue. Subfigures (b) and (e) show the projected views of (a) and (d) captured by a synthetic diagnostic "camera" near the end of the domain with a 30° view angle. Black lines mark the boundaries (gray lines mark the 30° view angle boundaries). All 3D plots and axial views are generated using the VisIt program. Subfigures (c) and (f) show transverse cross-sectional views of electron number density at y=10 cm. Subfigures (g) and (h) show the 1D profiles of electron and ion number densities along the line (y=10 cm, z=0 cm) for p=10 mTorr and p=1 mTorr, respectively.