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AZIMUTHAL INSTABILITIES AND STRUCTURES IN PENNING DISCHARGES *)

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The Penning, or reflex, discharge is one of the oldest plasma devices that nowadays finds a wide range of applications in modern plasma technologies, such as pressure gauges, neutron detectors, systems for mass species separation, ion sources for material processing, and others. In this configuration, a low-pressure cylindrical discharge in the axial magnetic field is maintained by the electron beam emitted from a hot cathode. Electrons are confined radially by the magnetic field and trapped axially by the electric field of the sheaths at the plates perpendicular to the magnetic field, the cathode and anti-cathode, which are typically biased to the same negative potential. The chamber walls serve as the anode. Ions are often unmagnetized, diffusing radially and axially to the walls, and can be extracted with additional biased electrodes. As an example of a discharge in a crossed electric and magnetic field, and due to its relative simplicity and ease of diagnostic access, the Penning configuration is also a useful testbed for studies of the physics of instabilities in ExB plasmas relevant to many applications, e.g., ion sources for neutral beam injectors and the physics of space plasmas. Despite its long history, the physics of the Penning discharge, especially the nature of its instabilities, is not fully understood and remains a topic of active research. Various instabilities that have been observed in such discharges can be detrimental to device performance. In this talk, we review the latest theoretical and some experimental results on fluctuations and structures in Penning configurations.

Many implementations of Penning configurations operate in regimes where the electric potential in the center of the discharge is negative relative to the anode. In this case, the electric field is inward and, thus, it is in the same direction as the density gradient. While the inward electric field is favorable for ion confinement, it is prone to the so-called Simon-Hoh (SH) instability. It is believed that the SH instability is generally responsible for the instabilities observed in many Penning discharges. Such instabilities may result in nonuniform ion fluxes which adversely affect applications in material processing. For these applications, regimes with an outward electric field are of interest, in which the SH instability is presumably suppressed; however, other mechanisms of drift-dissipative instabilities can be operative, particularly those driven by density gradients and collisions.

To investigate different instability regimes, we have performed numerical simulations of the Penning discharge with a 2D3V (radial–azimuthal) and a full 3D3V PIC/MCC models. The discharge is self-consistently supported by ionization due to the axial injection of electrons. Our 2D simulations show that a steady-state discharge can be supported in two different regimes with different types of observed azimuthal structures: a large-scale $m = 1$ spoke mode and multiple small-scale $m > 1$ spiral arm structures. The transition between these regimes is controlled by the mechanism of energy input to the discharge. The transition from spiral arms to the spoke regime occurs when the plasma potential in the center changes from weakly positive (or zero) to negative. The transition can also be induced by an increase in the magnetic field resulting in a well-developed $m = 1$ spoke mode with additional small-scale, higher-frequency $m > 1$ structures inside and around the spoke.

We also present the results of full 3D particle-in-cell simulations of a cylindrical Penning discharge with an emphasis on a specific regime in which the plasma potential in the center of the discharge is positive. We observe azimuthally rotating structures that overlap with axial fluctuations which are weakly correlated with azimuthal modes, so that the azimuthal modes rotate as a whole and do not show any axial shear. The spatial and temporal scales of the observed structures and fluctuations are characterized. The mechanisms of the underlying instabilities are suggested and discussed.

*) abstracts of this report in Russian