Rotating structures in low temperature magnetized plasma devices: spokes, electron vortices and others

Jean-Pierre Boeuf

Université de Toulouse, UPS, CNRS, INPT; LAPLACE (Laboratoire Plasma et Conversion d'Energie), 118 Route de Narbonne, 31062 Toulouse, France

In low temperature magnetized plasma sources, electrons are often strongly magnetized and confined by the magnetic field while ions are not. These sources are generally cylindrically symmetric and operate in a crossed electric field ***E*** and magnetic field ***B*** configuration where ***E***×***B*** is in the azimuthal direction. Various devices such as Hall thrusters for satellite propulsion, End-Hall ion sources, magnetrons for sputtering applications, Penning discharges, etc… operate in such configuration. In these devices, the large azimuthal electron drift can trigger instabilities leading to the formation of plasma structures rotating around the cylindrical axis. After a brief review of the observed rotating structures in several magnetized plasma sources, we focus on the results of Particle-In-Cell Monte Carlo Collisions (PIC MCC) simulations in devices with axial magnetic field and radial electric field such as cylindrical magnetrons. At pressure of a few mtorr (conditions of magnetron sputtering discharges), the simulations predict the existence of "spokes" or double layer ionization fronts rotating at a velocity close to the critical ionization velocity. At pressure lower than typically 0.1 mtorr (Penning gages can operate in this pressure range) a nonneutral plasma region is present in the electrode gap and electron vortices rotating around the cylindrical axis are observed in the simulations. The results presented in this lecture include recent work on rotating structures published in Frontiers in Plasma Physics[1].

1. *E*×*B* devices – Electron confinement and instabilities

In an *E*×*B* discharge device the external magnetic field is placed perpendicular to the applied electric field *E* and discharge current *J*. In regions of the discharge where the electric field is large (i.e. in the cathode sheath, or in the plasma itself in devices such as Hall thrusters where an electron emitting cathode is used) a large electron drift is established in the *E*×*B* direction. This direction must be closed on itself otherwise (when the *E*×*B* or *J*×*B* direction is perpendicular to a wall) electron confinement is broken by the Hall effect. Most magnetic discharge devices are therefore designed in such a way that the *E*×*B* direction is the azimuthal direction of cylindrically symmetric configuration. Such configurations are often called "closed-drift configurations" because the electron drift current in the *E*×*B* direction is closed on itself. Typical examples of closed-drift discharge devices are magnetron sputtering discharges and Hall thrusters. Note that there is precisely no Hall effect in a Hall thruster because of the closed-electron drift. On the other hand there is a Hall effect for example in the magnetic filter of a negative ion source for neutral beam injection in fusion applications because the *J*×*B* direction is perpendicular to a wall. This Hall effect limits electron confinement by the filter and is responsible for an asymmetry of the plasma properties[2].

According to classical, collisional electron transport theory, the electron mean velocity in the direction parallel to the applied field is

$$\mathbf{v}_E = \frac{e}{m\nu}\frac{1}{1+h^2}\boldsymbol{E}$$

while the electron drift in the *E*×*B* direction is

$$\mathbf{v}_{E\times B} = \frac{h^2}{1+h^2}\frac{\boldsymbol{E}}{\boldsymbol{B}}$$

$h = \frac{\Omega}{\nu} = \frac{eB}{m\nu}$ is the Hall parameter (Ω is the electron cyclotron angular frequency and ν is the electron collision frequency).

The Hall parameter is much larger than 1 (so that $\mathbf{v}_E \approx \frac{e}{m\nu}\frac{1}{h^2}\boldsymbol{E}$ and $\mathbf{v}_{E\times B} \approx \frac{\boldsymbol{E}}{\boldsymbol{B}}$) and is larger than 10^2 in typical *E*×*B* devices.

The electron residence time between cathode and anode is therefore considerably enhanced (the electron velocity parallel to *E* is reduced by a factor h^2) with respect to the non-magnetized case. The electron confinement in *E*×*B* devices is however not as good as predicted by the classical collisional transport theory above because of the development of instabilities.

Instabilities are ubiquitous in magnetized plasmas in a large range of plasma properties, from fusion plasmas, to space plasmas and low temperature plasma devices. These instabilities lead to the development of waves and field fluctuations that play the role of collisions in un-trapping electron trajectories, limit the efficiency of the electron confinement by the magnetic field and enhance electron transport across the magnetic field ("anomalous" transport).

In $E\times B$ discharge devices, instabilities can be triggered, for example, by the large electron drift in the $E\times B$ direction. These instabilities may lead to azimuthal charge separation and to the formation of a non-zero local azimuthal electric field that can in turn generate a cross-field electron drift in the direction parallel to the applied electric field and therefore decrease electron confinement.

2. Experimental evidence of rotating structures in $E\times B$ devices

There are numerous examples of research investigations related to rotating structures in low temperature $E\times B$ devices. Penning discharges used as ionization gages[3] were certainly among the first $E\times B$ devices to be thoroughly studied. At low pressure (below 0.1 mtorr) and large enough magnetic fields, the electron confinement time in the discharge can be much longer than the ion transit time and the discharge may be non-neutral (electron density larger than the ion density). In these conditions the well-known diocotron instability[4-6] can be present and play an important role in the discharge dynamics. This instability is associated with the formation of electron vortices[7, 8] rotating around the cylindrical symmetry axis. The diocotron instability has been studied mainly in pure electron plasmas[9, 10], i.e. under collisionless conditions where the electrons are injected from a hot cathode and confined in a Penning-Malmberg trap.

Important applications of $E\times B$ discharges concern ion sources for space propulsion, surface processing, and coating processes based on magnetron sputtering. In these applications, the gas pressure is typically in the 1-10 mtorr range, and most of the discharge volume is filled with a quasi-neutral plasma. In Hall thrusters azimuthally rotating spokes have been observed and described in the early work of Janes and Lowder[11] in the 1960s. These authors suggested that the rotation of the spoke is due to a coupling between the density non-uniformities and the ionization process. In a more recent work Ellison et al.[12] describe the observation of rotating spokes in a Hall thruster and discuss the role of the spokes in the anomalous electron transport across the magnetic field.

High power pulsed magnetrons for sputtering-deposition applications (High Power Impulse Magnetron Sputtering, HiPIMS), have been the subject of numerous publications in the last ten years. One of the topics discussed in these papers is the presence in the plasma of these $E\times B$ discharge devices of rotating structures, termed as "rotating spokes"[13-16] and described as rotating regions of enhanced ionization associated with an electric potential structure with an azimuthally directed electric field. Due to the large and pulsed power used in these devices, the analysis of the physical processes responsible for the presence of spokes is difficult and different mechanisms are invoked to explain these structures and their dynamics (e.g. neutral depletion[17], secondary electron emission[18]).

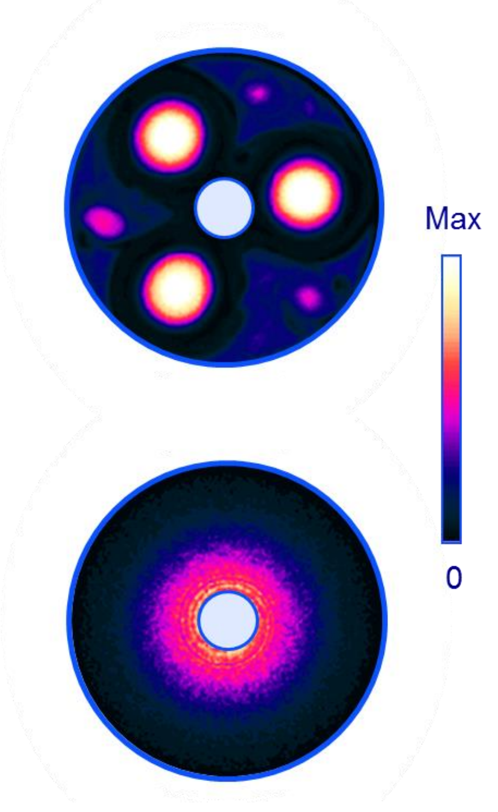

Figure 1: Distributions of the electron density (top) and ion density (bottom) in a cylindrical magnetron discharge at low pressure (0.05 mtorr, argon, 1 kV, 50 mT, cathode diameter 1 cm, anode diameter 5 cm), from a 2D PIC MCC simulation. The plasma is non-neutral (unit for the electron density: $3\mathrm{x}10^{15}$ m^{-3}, ion density: $0.2\mathrm{x}10^{15}$ m^{-3}). Three electron vortices are apparent and rotate clockwise around the cylindrical axis while the non-magnetized ions are simply accelerated toward the cathode.

The rotating structures observed in HiPIMS and other $E\times B$ devices present similarities with the rotating spokes reported in pulsed high-power homopolar $E\times B$ discharges studied in the 1970s-1980s in the context of fusion and of the Critical Ionization Velocity concept. This topic has also been the subject of a very abundant literature (see, e.g. the papers by Danielsson[19], Danielsson and Brenning[20], Brenning et al.[21, 22] and Piels et al.[23, 24]). The Critical Ionization Velocity (CIV) is a very interesting concept introduced by Alfven in a model of the formation of the solar system. This model considers a neutral gas cloud falling, due to the sun gravity, on a magnetized plasma. Charge separation occurs due to momentum transfer from neutral species to ions, leading to a potential drop in the plasma. If the gas velocity reaches a critical value (CIV) corresponding to equality between kinetic energy of the neutral species and their ionization energy threshold, the potential drop is sufficient to heat the electron and lead to rapid ionization. The region of charge separation constitutes a double layer and an ionization front. Ionization of the falling gas prevents it from falling further in the gravitational field of the sun and it has been suggested by Alfven that this mechanism can explain the formation of planets.

3. Kinetic simulations of rotating structures

Particle-In-Cell Monte Carlo Collisions simulations have been performed in the conditions of a cylindrical magnetron geometry with two concentric electrodes and an axial magnetic field. The simulations are two-dimensional so that only "flute-type" instabilities (i.e. homogeneous in the axial direction) can be described. Possible charged particle losses at the ends of the plasma column can be taken into account. The simulations have been performed in different gases, for gas pressure between 0.05 mtorr and 10 mtorr, an electrode gap of 2 to 3 cm and an inner electrode diameter of 1 cm, applied voltages between a few 100 V and 3 kV, and magnetic field in the 10-50 mT range.

At pressure on the order or below 0.1 mtorr, the plasma exhibits large non-neutral regions and the simulations predict the formation of rotating electron vortices (see Fig. 1) with properties very similar to those of the experiments reported by Kervalishvili[7, 8].

At pressure above a few mtorr, a neutral plasma region forms between the cathode and anode sheaths. 1D PIC MCC simulations provide stable solutions in these conditions, with a relative large potential drop in the plasma (due to the reduced electron conductivity). Such solutions are however not stable in 2D, and the 2D PIC MCC simulations[1, 25] predict the formation of a rotating spoke (see Fig. 2) whose properties are similar to those of the phenomenological model of Piel et al.[23] related to the CIV concept.

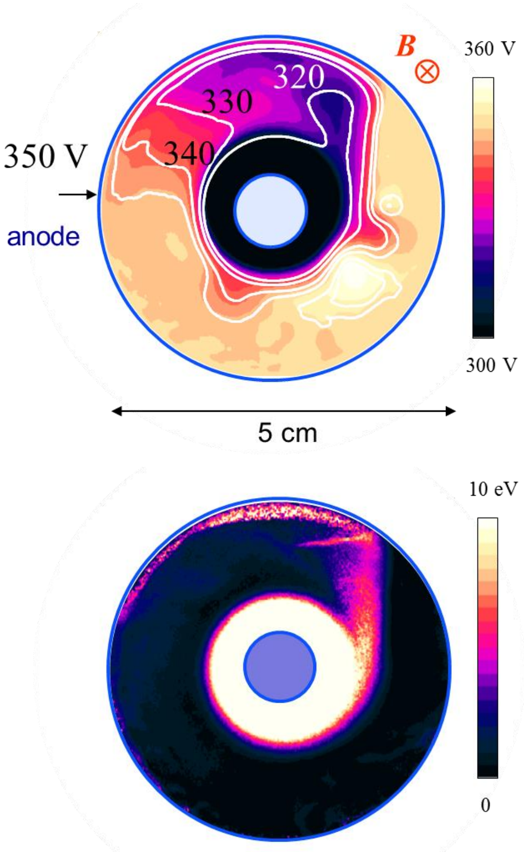

Figure 2: Space distribution of the electric potential (top) and ion mean energy obtained at a given time of the 2D PIC MCC simulation of a cylindrical DC magnetron discharge (10 mtorr, Argon, 30 mT, 350 V; cathode diameter 1 cm, anode diameter 5 cm). Voltages below 300 V (i.e. in the cathode sheath) are not represented. The ion mean energy is plotted only below 10 eV (the ion mean energy in the cathode sheath is much larger, up to more than 200 eV). The spoke is located in the region of potential drop and is apparent on the ion mean energy distribution (acceleration of the plasma ions by the azimuthal field). The spoke is rotating clockwise.

The existence of this instability is consistent with the theory of the so-called Simon-Hoh[26, 27] instability or modified Simon-Hoh instability[28] which states that under conditions where the electron and ion $E\times B$ drift velocities are different (this is the case here since ions are practically not magnetized) instabilities form when the plasma density gradient and electric field are in the same direction. This causes a charge separation between electrons and ions and therefore the formation of a perturbed azimuthal electric field.

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