Nonadiabatic energization of electrons in spokes observed in magnetrons with a nonuniform magnetic field

D. Eremin(*)[1], L. Vogelhuber[1], J. Kallähn[1], K. Köhn[1], D. Krüger[1], L. Xu[2], R.P. Brinkmann[1]

[1] *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, 44801, Bochum, Germany*
[2] *Department of Physical Science and Technology, Soochow University, 215006, Suzhou, China*
(*) Denis.Eremin@rub.de

Self-organized spoke structures are observed in many partially magnetized (with magnetized electrons, but unmagnetized ions) $\mathbf{E} \times \mathbf{B}$ plasmas such as planar and cylindrical magnetrons, Hall thrusters, Penning discharges, and others. They represent rotating zones of increased ionization and excitation leading to enhanced light emission. One of the fundamental questions is therefore where do energetic electrons causing these phenomena come from and what is the underlying energization mechanism. Since the magnetic field does no work, electrons gain energy only from the electric field. To the leading order of the drift-kinetic theory, electron guiding centers move along the equipotential surfaces with the $\mathbf{E} \times \mathbf{B}$ drift. In this case, electron kinetic energy oscillates with an amplitude determined by a potential difference over a Larmor radius [1]. However, this mechanism is too weak to create a strong localized population of electrons associated with a spoke structure. It was recently proposed that an additional electron heating occurs in a nonuniform magnetic field, where ∇B drift motion of the electron guiding center carries an electron into an area of increased potential at the spoke front [2]. It can be shown that the corresponding heating mechanism is adiabatic and therefore limits the electron energy boost by the need to conserve the magnetic moment (increase in the perpendicular kinetic energy is related to the increase of the magnetic field along the electron trajectory, rather than being determined by the potential jump). Indeed, the rate of energy change due to the guiding center motion is $-e\mathbf{E} \cdot \mathbf{v}_{\nabla B} = \frac{mv_\perp^2}{2B} \frac{\mathbf{E}\cdot[\mathbf{B}\times\nabla B]}{B^2}$, but on the other hand it can be written as $\frac{d}{dt}\frac{mv_\perp^2}{2} = \frac{d}{dt}(\mu B) = \mu(\mathbf{v}_{\mathbf{E}\times\mathbf{B}} \cdot \nabla)B$, which is derived under the ansatz of the magnetic moment conservation. At the same time, potential jumps at the spoke front, seen in both experimental studies and simulations of DC magnetrons, can be as large 100 eV and the simulations indicate existence of electrons with the corresponding energy. A question arises whether such a big increase in energy can be obtained while electron magnetic moment is held constant.

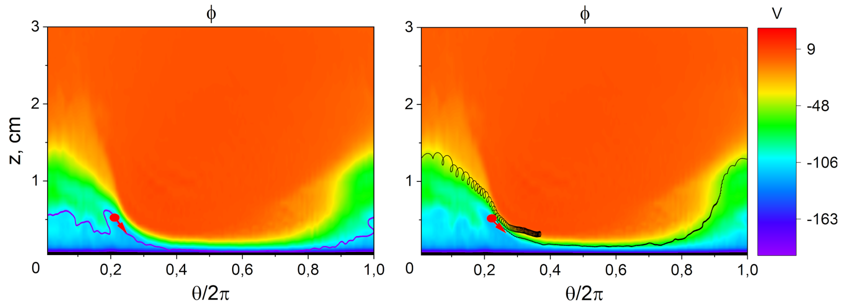

Fig. 1: Typical electron trajectories: quasiperiodic trajectory (left) of an electron far from the potential jump and trajectory of an energized electron crossing the potential jump (right). The cathode is at the bottom, the anode is at the top, the magnetic field is orthogonal to the page, and the magnetic field flux density decreases from the cathode.

To answer this question, the authors performed a 2D (θ, z) electrostatic PIC simulations with an implicit energy-conserving ECCOPIC2S-M code [3, 4] exhibiting formation of spokes. The simulation setup was similar to the one used in [2]. After the spokes were fully formed, the electrostatic potential was taken at a chosen time and thereupon was held fixed, whereas motion of test electrons was investigated in such a prescribed potential. This was done to eliminate possible electron heating mechanisms resulting from time-dependent electric fields (e.g., due to microinstabilities). It was explicitely checked that the total energy consisting of a sum of the kinetic and potential energies was constant for all electrons to a good accuracy (not shown). Fig. 1 shows orbits of a typical electron traversing a quasiperiodic orbit away from the spoke-related sharp potential jump and close to the cathode and of an electron which crosses the potential jump and thus gains a lot of energy, which is evidenced by the Larmor radius growth (note, however, that the Larmor radius is decreased as the electron further enters an area of a larger magnetic field).

Fig. 2 reveals the electron heating explicitly by comparing properties of the first particle (top row) and the second particle (bottom row). Using the dependence of electron coordinates on time (leftmost column), one can see that the first electron exhibits an adiabatic evolution of energy, showing smooth evolution of the average energy as the ∇B drift pushes the electron into an area of elevated potential as well as the amplitude of its oscillations as the electron moves into an area of increased electric field underneath the potential hump, in full agreement with [2] and [1]. As expected, the magnetic moment extracted from the simulation remains approximately constant and equal to its initial value. It is worth noting that for a proper evaluation of the magnetic moment various guiding center drifts must be subtracted [5]. These were evaluated in the simulation results by identifying the rotation period as the time interval between the velocity vector passing the same angle and averaging the electron velocity.

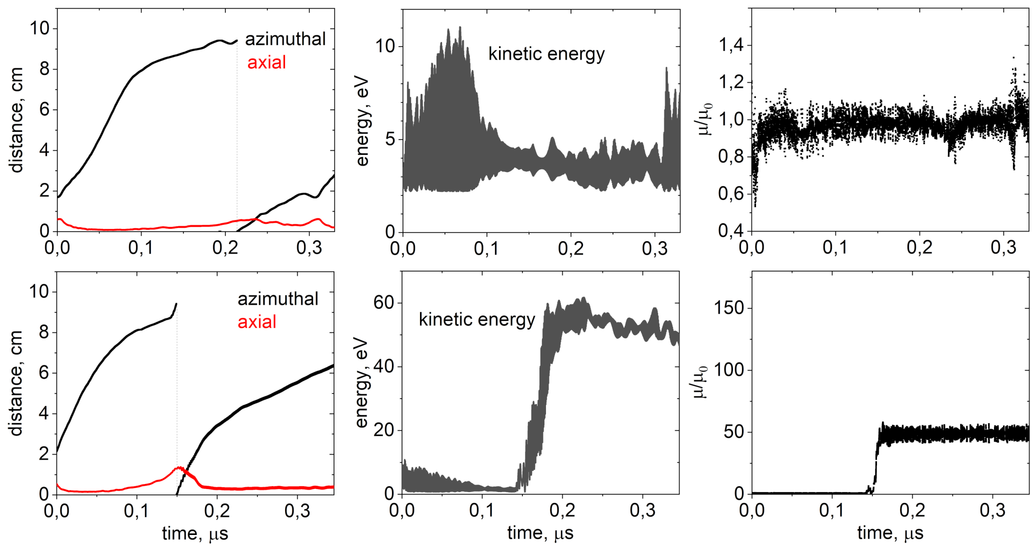

Fig. 2: Properties of the quasiperiodic (top row) and energized (bottom row) electron orbits shown in Fig. 1: coordinate evolution (left), kinetic energy (middle), and ratio of the magnetic moment to its initial value (right).

By inspecting the energized electron data (Fig. 2, bottom row) one can see that it acquires a large energy of 60 eV related to the potential jump at the spoke front. One can also see that in this case the electron's magnetic moment experiences a violent jump and becomes 50 times larger than its initial value. It clearly indicates that the corresponding energization mechanism is nonadiabatic and thus cannot be ascribed to the ∇B energization mechanism suggested in [2]. It can be seen that the electron energization consists of two phases, nonadiabatic heating, when electron perpendicular energy grows much faster than the magnetic moment conservation allows, followed by an adiabatic energization, which is related to the growth of the perpendicular velocity as the electron goes into a region of increased magnetic field flux density closer to the cathode. The existence of the nonadiabatic phase in the energization mechanism enables much stronger energy gains stored in the Larmor rotation compared to [2], which are governed by the large potential jumps in DC magnetrons and not the magnetic field nonuniformity. From Fig. 1 it can also be seen that the corresponding energized electron ends up on the other side of the potential jump, exactly where the maximum ionization is observed in simulations (not shown). One can therefore expect this mechanism to be important for the spoke physics.

[1] D. Eremin et al., *Plasma Sources Sci. Technol.* **32** (2023) 045007
[2] J.-P. Boeuf, M. Takahashi, *Phys. Rev. Lett.* **124** (2020) 185005
[3] D. Eremin, *J. Comp. Phys.* **452** (2022) 110934
[4] D. Eremin et al., *Plasma Sources Sci. Technol.* **32** (2023) 045008
[5] C.D. Stephens, R.W. Brzozowski, III, F. Jenko, *Phys. Plasmas* **24** (2017) 102517