PIC/MCC modeling of the dynamics of rotating spokes in a Penning discharge

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Penning discharges are plasma sources generated inside a cylinder with a large geometrical aspect ratio (length over radius) and with a magnetic field aligned with the longitudinal axis [1]. The magnetic field strength is sufficiently large to magnetize the electrons but not necessarily the ions. In such plasma configurations, the boundary conditions can greatly modify the plasma properties. Electrons, being strongly magnetized, are attached to a field line which is short-circuited at both ends of the cylinder by either a biased metal plate or a dielectric surface. Biasing negatively the end-plates for instance will increase the residence time of the electrons inside the plasma discharge to a point where their mobility might be lower than the one of their ion counterpart. The plasma potential will then eventually become a well to confine electrostatically the ions and hence keep the whole plasma quasi-neutral. In such a situation, the plasma will become unstable and lead to the formation of large-scale rotating structures in the non-linear saturated regime. These structures, so-called spokes, rotate typically at a frequency of the order of 10's of kHz depending on the mass of the ions [2,3].

In this paper, we will simulate a Penning discharge powered by an electron beam using an explicit Particle-In-Cell (PIC) model with Monte-Carlo-Collisions (MCC) [4]. The algorithm is parallelized with both OpenMP and MPI libraries and can run on supercomputers. An arbitrary physical chemistry can be modeled. We will describe in detail the dynamics of the rotating spoke in 2D (i.e., assuming a Penning discharge of infinite length) for Helium as a background gas and discuss the effect of the boundary conditions on the plasma behavior in 2.5D and 3D. A 2.5D configuration corresponds to a model where particle losses in the third virtual dimension, parallel to the magnetic field lines (i.e., along the discharge axis), are calculated in a simplified manner: ion losses are evaluated by deducing a loss frequency from the local Bohm velocity while the electrons are followed in 3D and assumed absorbed at the boundary surface if their axial kinetic energies exceed the potential difference between the plasma and wall potentials. The numerical mesh for the plasma potential is 2D and the electric field along the magnetic field is null by assumption. Only the potential drop is considered to calculate electron losses and the fastest electrons, as in a normal ion sheath, are removed locally from the plasma. The plasma density is hence an average over the axial discharge length. We will compare the predictions from 2.5D and 3D models. We will use the latter to describe the plasma dynamics along the magnetic field lines and assess whether the assumption of a flute mode along that direction for the spoke is indeed valid.

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