Spatiotemporal Characteristics of Charged-Particle Swarms in Orthogonal Electric and Magnetic Fields

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***Abstract*—Spatially resolved transport properties of a swarm of charged particles in spatially homogeneous and orthogonal dc electric and magnetic fields are investigated using a Monte Carlo simulation technique. The transient spatial profiles of the density and energy distribution function demonstrate an initial periodic structure of similar physical origin to the Franck–Hertz oscillations. It is found that, independent of the presence of a magnetic field, the spatial density profiles of the swarm relax to a Gaussian profile after a sufficient time.**

***Index Terms*—Distribution function, magnetic fields, monte carlo simulation, swarms, transport coefficients.**

RECENT PROGRESS in the developments of plasma processing tools has led to a resurgence of interest in fundamental swarm studies. In many plasma sources where the discharge is sustained and controlled by electric $(\mathbf{E})$ and magnetic $(\mathbf{B})$ fields, the typical distances for electron energy and momentum relaxation are comparable to the plasma source dimensions. Consequently, the transport properties at a given point are no longer a function of instantaneous fields. This is the case for a variety of magnetized plasma discharges where, before the electrons become fully relaxed, it is likely that the electrons will be reflected by the sheath or collide with the wall [1]. In the context of swarm studies, the spatial variation of the average energy along the swarm has played a central role in the explanation of many phenomena, including those associated with the implicit and explicit effects of nonconservative collisions and the anisotropic nature of the diffusion [2]. In this paper, as a part of our ongoing investigations of charged-particle transport in $\mathbf{E}$ and $\mathbf{B}$ fields, we study the effect of varying $\mathbf{B}$ ($\mathbf{E}$ defines the x-axis while $\mathbf{B}$ lies along the z-axis) on the spatiotemporal development of an infinite swarm under hydrodynamic conditions.

In this paper, we apply a Monte Carlo simulation code that follows a large number of particles (typically 10^5–10^6) through a neutral gas under the influence of uniform and crossed electric and magnetic fields. It is assumed that the charged-particle swarm develops in an infinite space. At time $t = 0$, electrons are initially released from the origin according to the Maxwellian velocity distribution with a mean starting energy of 2 eV. Electrons gain energy from the external electric field and dissipate it through collisional transfer to the neutral gas molecules by elastic and different types of inelastic collisions. Calculations have been performed for the ionization model of Lucas and Saelee [3]. We consider the reduced electric field E/n_0 (where n_0 is the gas number density and is set to 3.54×10^{22} m^{-3}, which corresponds to the pressure of 1 torr at 273 K) of 50 Td $(1\ \mathrm{Td} = 10^{-21}\ \mathrm{V \cdot m^2})$ and magnetic field range of 100–500 Hx $(1\ \mathrm{Hx} = 10^{-27}\ \mathrm{Tm^3})$. Rather than presenting a full review of our Monte Carlo simulation technique, we highlight hereinafter some important points associated with the sampling technique of spatially resolved data and refer the reader to [2] for a detailed discussion.

In order to sample spatially resolved transport parameters under hydrodynamic conditions, we have restricted the space and divided it into cells. Every cell contains 100 points, and these points are used to sample spatial parameters of the electron swarm. This concept of our code allowed us to follow the development of the swarm in both real spaces and normalized to 6σ, where σ is the standard deviation of the Gaussian distribution in space. The spatially resolved electron transport properties, including the average energy/velocity, have been determined by counting the electrons and their energies/velocities in every cell. Therefore, we may follow the spatial profiles of electron positions, as well as the spatial profiles of the average energy/velocity, as they develop in space and time and within the swarm.

Fig. 1 shows the 3-D plots of the spatial density profiles of particles and spatially resolved distribution function along the electric field direction as a function of B/n_0 for the instants 0.1 and 5 μs. For the instant 0.1 μs, the existence of oscillatory features in the profiles of spatial distribution of particles and distribution function is clearly evident. The transient spatial structures in the energy distribution functions are reflected in the transient spatial structures in the density profiles—the nature of which is similar to those observed in the steady-state Townsend conditions and Franck–Hertz experiments [3]. The basic characteristics of these oscillations are controlled by strong competition between elastic and inelastic energy losses [3].

When a magnetic field is applied, the swarm is more localized in space due to the explicit orbital effect which acts to inhibit diffusion in a plane perpendicular to the magnetic field.

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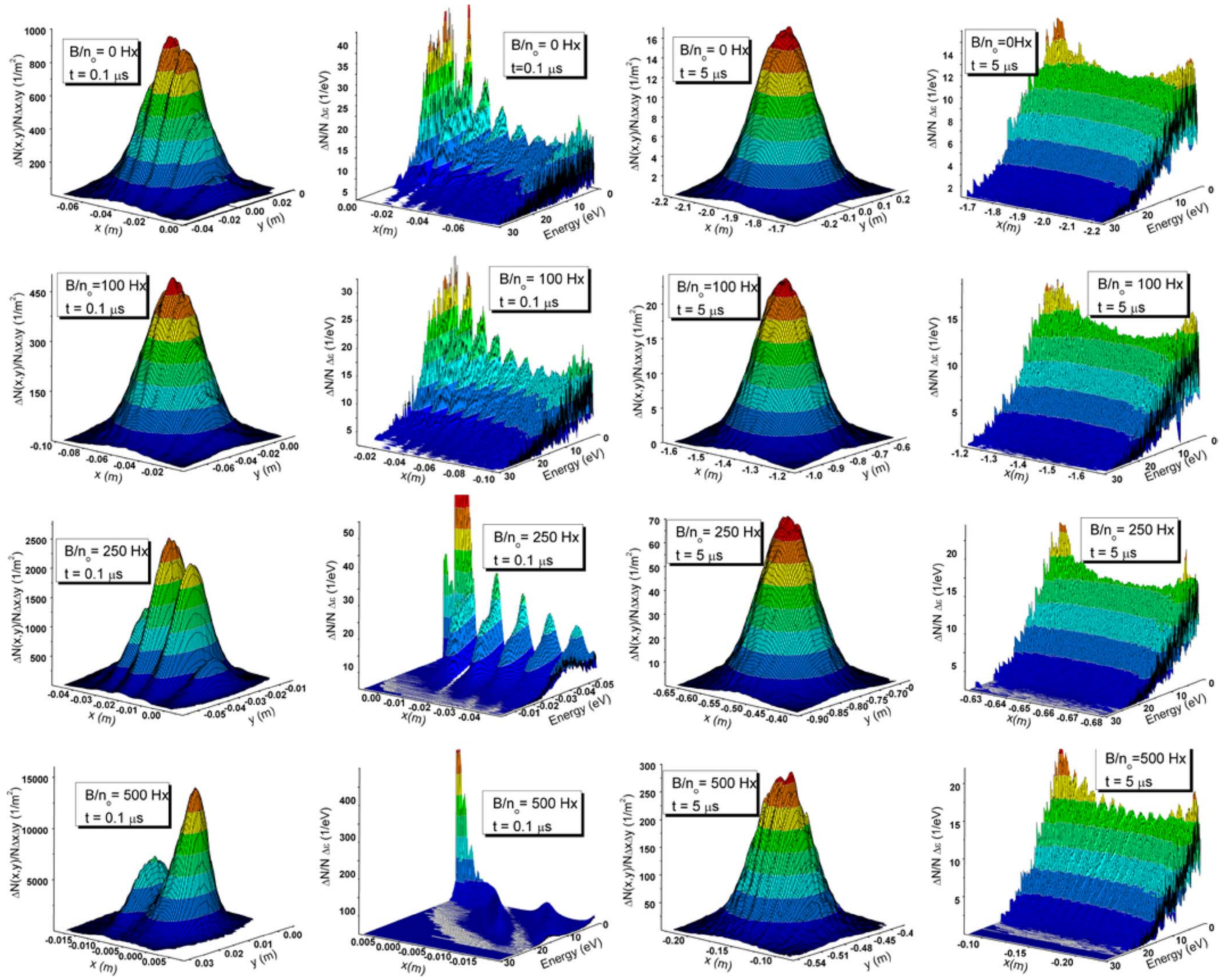

Fig. 1. (Columns I and III) Spatial density profiles and (columns II and IV) spatially resolved distribution functions as functions of B/n_0 for the instants (columns I and II) 0.1 μs and (columns III and IV) 5 μs.

From the profiles of the distribution function, it is seen that the most energetic electrons are localized at the leading edge of the swarm. For the instant 5 μs, the oscillatory feature is significantly reduced due to the active role of elastic collisions which tend to damp the oscillatory behavior, as evidenced by the trend of the spatial distributions of particles to attain a Gaussian profile. From the profiles of the distribution functions, we observe that the sharp peaks at the front of the swarm have disappeared, and energetic electrons are regrouped almost on an equal footing along different spatial positions. In conclusion, the explicit impact of the magnetic field has a complex impact on the temporal evolution of spatial structure within the swarm, and further studies are required to understand the physics of the observed phenomena.

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