Visualization of Electron Transport Coefficients in RF Electric and Magnetic Fields Crossed at Arbitrary Angles

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***Abstract*—The Boltzmann equation for charged particle swarms in gases subject to arbitrarily oriented spatially homogeneous and time-dependent electric and magnetic fields is solved by a recently developed multiterm theory, and attention is focused on the portrayal of the electron transport properties. Temporal variations of the electron transport data are presented for the Reid ramp model gas in varying configurations of electric and magnetic fields for a fixed field frequency and amplitudes of the electric and magnetic fields.**

***Index Terms*—Boltzmann equation, RF electric and magnetic fields, swarms, transport coefficients.**

NONEQUILIBRIUM low-temperature plasma discharges sustained and controlled by radio-frequency (RF) electric and magnetic fields are widely used in many scientific and industrial applications [1]. In many modeling efforts of the collision-dominated bulk region of these plasmas, the description of electron kinetics has turned out to be the most difficult and time-consuming part. First, the electron kinetics develops at the shortest time scales compared to other relevant processes, and due to small frequency of electron–electron collisions, the velocity distribution function exhibits a distinct nonequilibrium nature and can be far from Maxwellian. Second, it is well known that, within these discharges, the fields can vary in space and orientation depending on the type of discharge and transport/plasma properties are essentially nonlocal in both space and time. There is no easy way out—studies of nonlocal and kinetic effects in electron transport in varying configurations of RF electric and magnetic fields require a full kinetic approach based on contemporary and accurate techniques for solving the Boltzmann equation.

Solution of the Boltzmann equation for charged particle swarms under the influence of time-dependent electric and magnetic fields has been recently detailed by Dujko *et al.* [2], and we emphasize here only the following critical points: 1) The angular dependence of the phase space distribution function in velocity space is represented in terms of a spherical harmonic expansion; 2) the speed dependence of the phase space distribution function is resolved through an expansion about a Maxwellian at an arbitrary time-dependent temperature in terms of Sonine polynomials; and 3) under hydrodynamic conditions, a sufficient representation of the space dependence and implicit time dependence is an expansion of the distribution function in terms of powers of the density gradient operator. In this paper, we consider the Reid ramp model [3] for electrons in RF electric and magnetic fields. The applied reduced angular frequency Ω/n_0 is set to 2×10^{-14} rad $\cdot$ m$^{-3} \cdot$ s^{-1} while the electric and magnetic field amplitudes are 12 Td (1 Td $= 10^{-21}$ V $\cdot$ m^2) and 1000 Hx (1 Hx $= 10^{-27}$ T $\cdot$ m^3), respectively. We employ a coordinate system where $\mathbf{E}$ defines the z-axis while $\mathbf{B}$ lies in the y–z plane, making an angle ψ with respect to $\mathbf{E}$. Calculations have been performed only for angles between 0 and $\pi/2$ rad. Extension to other angles can be made through the use of symmetry properties outlined in our previous publications [2], [3].

Fig. 1 shows the temporal variations of the drift velocity components and diagonal elements of the diffusion tensor as a function of the angle ψ between the fields. The manifestation of these complex temporal profiles in RF $\mathbf{E}$ and $\mathbf{B}$ fields is distinctively nonlocal in time and not predictable from the steady-state dc results. The figures illustrate the various symmetry properties which must exist, e.g., $W_x = 0 = W_y$ and $D_{xx} = D_{yy}$ for $\psi = 0^\circ$. For W_z, we observe for $\psi = 0$ a profile that oscillates at the fundamental frequency of the field. As the angle ψ is increased, we observe the introduction of additional temporal complexity in the profiles, and this introduction is present in other transport properties as well. In addition to the explicit orbital effects of changing, there is also additional contribution resulting from the cooling effect of increasing ψ. This reduces the average collision frequency and, hence, the ability of the swarm to respond to changes in the field. Consequently, the additional structure in the RF profiles then follows [3]. In contrast to W_y and W_z, the asymmetry in the W_x profiles is clearly evident and further increased for an increasing ψ. This is a clear

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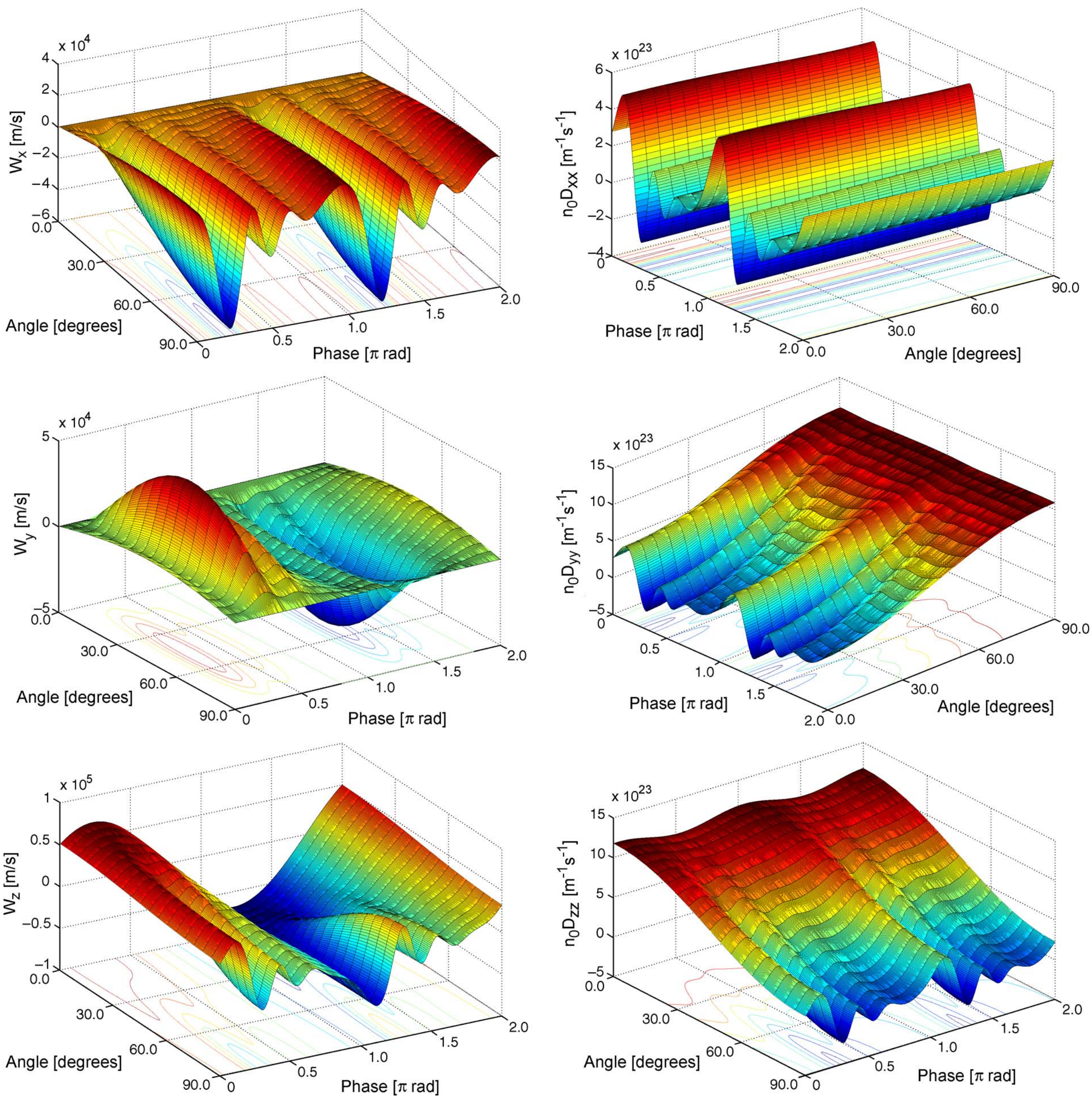

Fig. 1. Temporal variations of the drift velocity components and diagonal elements of the diffusion tensor for electrons in Reid ramp model gas as a function of the angle between the fields.

sign that the Lorentz force induces macroscopic drift along the $\mathbf{E} \times \mathbf{B}$ direction while, along the other directions, the electrons simply oscillate around the initial positions. Perhaps, the most striking phenomenon is the presence of "negative" diffusivity in the profiles of the diagonal elements of the diffusion tensor. For $n_0 D_{xx}$, the negative excursion occurs in the profiles for all ψ, while for $n_0 D_{yy}$, the negative diffusivity occurs in the limit of parallel fields and small angles between the fields. For $n_0 D_{zz}$, the opposite situation holds: The diffusion becomes transiently negative in the limit of an orthogonal field configuration and large ψ. Having in mind these phenomena and the fact that the code has been tested against all known benchmarks [2], [3], the present data may be used for further testing of new codes and plasma models.

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