Two-Peaked Velocity Distribution Function of Electrons in Carbon Tetrafluoride in Crossed Electric and Magnetic Fields

Hirotake Sugawara, Akinori Oda, and Yosuke Sakai

***Abstract*—Monte Carlo simulation shows that the electron velocity distribution function (EVDF) in CF_4 in crossed electric and magnetic fields ($\boldsymbol{E} \times \boldsymbol{B}$ fields) has two peaks at low E/B values. The EVDF peaks are formed around a pair of points in velocity space at which electrons are stationary against the acceleration under the $\boldsymbol{E} \times \boldsymbol{B}$ fields and scattering by collisions with CF_4 molecules. The stationary points appear when the E/B value is lower than the electron speed at which the total electron collision frequency in CF_4 takes its minimum.**

***Index Terms*—Crossed electric and magnetic fields, electron velocity distribution function, stationary points.**

ELECTRON swarm behavior in crossed electric and magnetic fields ($\boldsymbol{E} \times \boldsymbol{B}$ fields) has been studied as a fundamental property of magnetized plasmas. Electron gyration is one of the most characteristic effects caused by $\boldsymbol{E} \times \boldsymbol{B}$ fields, and it induces a shift of the electron velocity distribution function (EVDF). Attempts to visualize such a shifted EVDF at arbitrary angles between $\boldsymbol{E}$ and $\boldsymbol{B}$ are found, e.g., in [1], [2] for CH_4 and CO_2. We report in this paper a new finding that the EVDF in $\boldsymbol{E} \times \boldsymbol{B}$ fields becomes two-peaked in CF_4 at low E/B values because of the presence of the Ramsauer–Townsend minimum (RTM) and the two peaks fuse when the shift reaches a limit. The mechanism to make the EVDF two-peaked is explained on the basis of stationary points in velocity space against the electron acceleration and scattering.

Assuming the $\boldsymbol{E} \times \boldsymbol{B}$ field configuration as $\boldsymbol{E} = (0, 0, -E)$ and $\boldsymbol{B} = (0, B, 0)$ as given in [2], [3], the motion equation $\mathrm{d}\boldsymbol{v}/\mathrm{d}t = (-e/m)(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$ for an electron free flight yields

$$v_x(t) = E/B + v_z(0)\sin\omega t + [v_x(0) - E/B]\cos\omega t \quad (1)$$

$$v_y(t) = v_y(0) \quad (2)$$

$$v_z(t) = v_z(0)\cos\omega t - [v_x(0) - E/B]\sin\omega t. \quad (3)$$

Here, $\boldsymbol{v} = (v_x, v_y, v_z)$, E/B is the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity and $\omega = eB/m$. In velocity space, the electrons rotate around an axis $(v_x, v_z) = (E/B, 0)$. This axis consists of fixed points for the rotation. Fig. 1 is a schematic of the electron rotation. Note here that a fixed point in velocity space corresponds to a uniform motion in real space and the rotation is observed as a gyration. Electron–molecule collisions cause an electron jump from one orbit to another. However, the collision probability is small around the RTM of CF_4. Here, let us define v_m as the electron speed at which the total electron collision frequency in CF_4 takes its minimum. When the rotation axis has intersections with a sphere $|\boldsymbol{v}| = v_\mathrm{m}$ in velocity space, the intersections are stationary against both of electron acceleration and scattering (Fig. 1). It is predicted that electrons concentrate around the stationary points and they form a two-peaked EVDF, because the action of the $\boldsymbol{E} \times \boldsymbol{B}$ fields and collisions to move electrons away from the regions is weaker than that in their periphery.

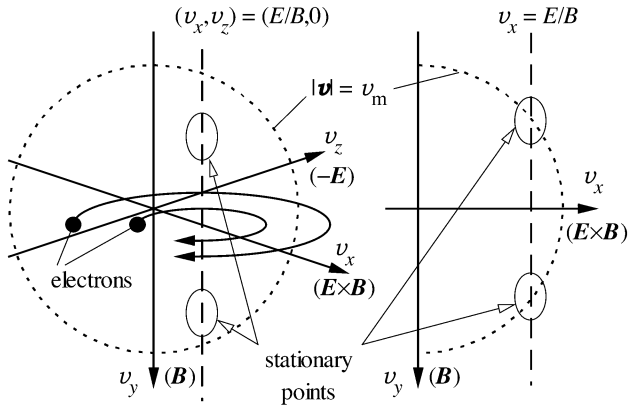

Fig. 1. Rotary motion of electrons in velocity space and stationary spots where the EVDF cores appear.

In order to confirm the appearance of the two-peaked EVDF in CF_4, we have performed a Monte Carlo simulation (a null-collision method with a time-saving technique customized for CF_4, [3]). The electron collision cross section set of CF_4 has been taken from [4]. The RTM of CF_4 lies around 0.15 eV. However, the RTM is covered by a vibrational excitation cross section of CF_4. Its onset energy is 0.078 eV, which determines v_m as $v_\mathrm{m} = 0.28 \times v_1$. Here, v_1 is the electron speed associated with 1 eV, and an electron energy ε is converted into the corresponding speed v as $v/v_1 = (\varepsilon/\varepsilon_1)^{1/2}$ with $\epsilon_1 = 1$ eV. The gas molecule number density N has been set at 3.54×10^{16} cm^{-3} (i.e., a gas pressure of 133 Pa at 273 K), B has been fixed at 7.5 mT, and E has been varied from 8 to 13 V/cm. These B and E values correspond to E/B values in a range from $0.18 \times v_1$ to $0.29 \times v_1$, B/N of 212 Hx (1 Hx $= 10^{-21}$ T cm^3) and E/N of 22.6–36.7 Td (1 Td $= 10^{-17}$ V·cm^2). More than 500 000 samples have been taken for each simulation condition.

Fig. 2 shows cross sections (side views) of the EVDF at a plane of $v_z = 0$ and projections (top views) of the EVDF to the

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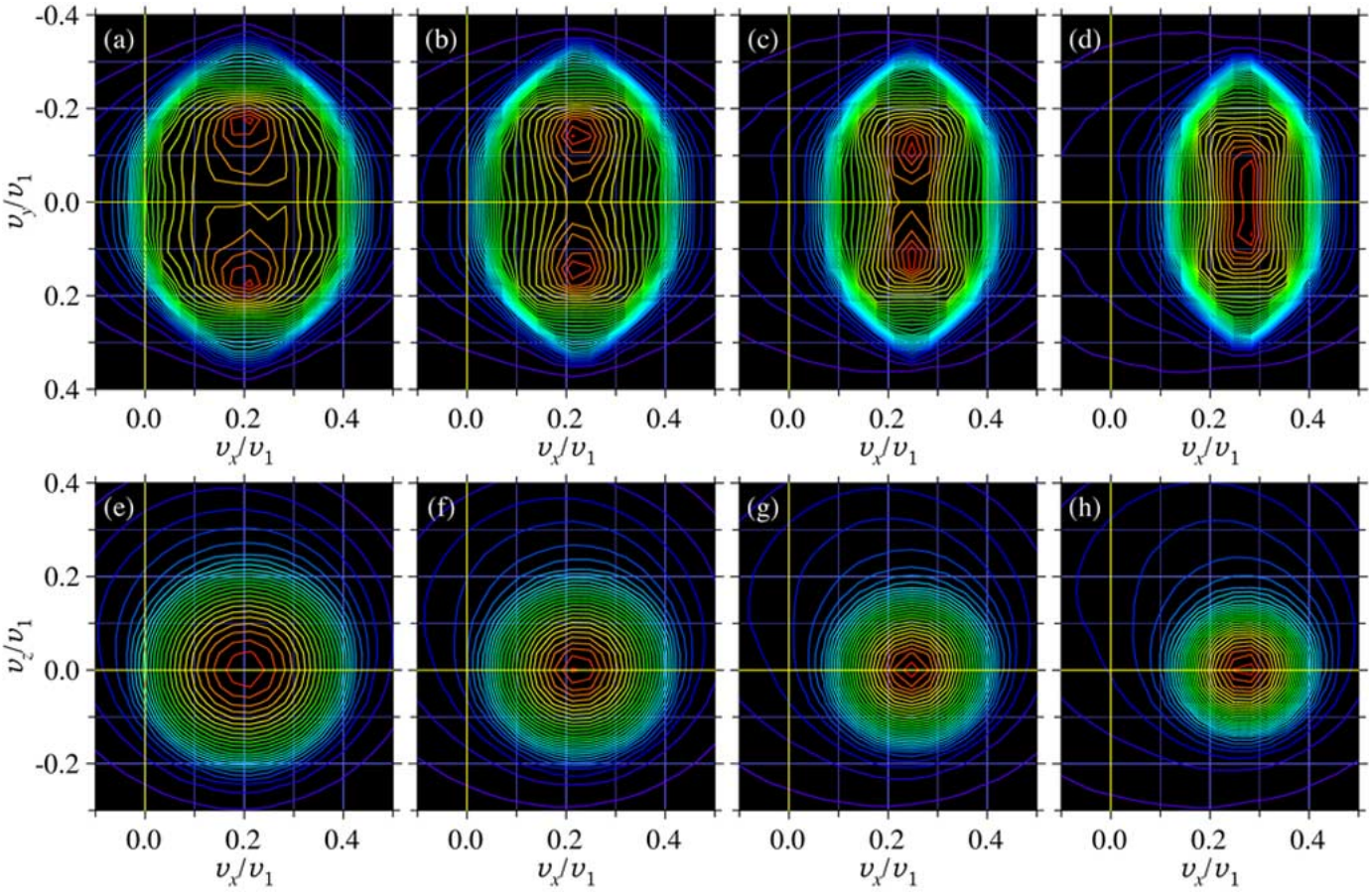

Fig. 2. Contour plots of the EVDF in CF_4 in $\boldsymbol{E} \times \boldsymbol{B}$ fields: (a)–(d) cross sections at the $v_x - v_y$ plane ($v_z = 0$, side views); and (e)–(h) projections to the $v_x - v_z$ plane ($v_y = 0$, top views). $B/N = 212$ Hx; (a) and (e), $E/N = 25.4$ Td; (b) and (f), 28.2 Td; (c) and (g), 31.1 Td; and (d) and (h) 33.9 Td.

plane of $v_y = 0$ at various E/N values. In Fig. 2(a)–(c), the peaks are at about $0.27 \times v_1$ away from the origin $\boldsymbol{v} = (0, 0, 0)$ of velocity space. This distance is close to v_{m}. The peaks of the EVDF moves toward the $+v_x$ direction from Fig. 2(a) to (d) and from Fig. 2(e) to (h) following the shift of the rotation axis of $(v_x, v_z) = (E/B, 0)$. Note that the EVDF would move toward the $+v_z$ direction when $B = 0$. The two-peaked structure is observed in Fig. 2(a)–(c), and the peaks fuse in Fig. 2(d). The distance between a peak and the origin of velocity space is kept almost constant, which supports the explanation that the two peaks appear around the intersections between the rotation axis and the sphere $|\boldsymbol{v}| = v_{\mathrm{m}}$.

In conclusion, we have visualized two-peaked EVDF in CF_4 in $\boldsymbol{E} \times \boldsymbol{B}$ fields and explained the mechanism to form it. The two peaks of the EVDF appear around the stationary points for electron motion in velocity space. The stationary points are the intersections between the axis of electron rotation under the action of $\boldsymbol{E} \times \boldsymbol{B}$ fields and a sphere $|\boldsymbol{v}| = v_{\mathrm{m}}$ of the electron speed associated with the minimum collision frequency.

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