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Binary Nature of Collisions Facilitates Runaway Electron Generation in Weakly Ionized Plasmas

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Dreicer generation is one of the main mechanisms of runaway electrons generation, in particular during tokamak startup. In fully ionized plasma it is described as a diffusive flow from the Maxwellian core into high energies under the effect of the electric field. In this work we demonstrate a critical role of the non-differential nature of inelastic collisions in weakly ionized plasma during tokamak startup, where some electrons experience virtually no collisions during acceleration to the critical energy. We show that using a mean friction force model for such collisions can underestimate the Dreicer generation rate by several orders of magnitude.

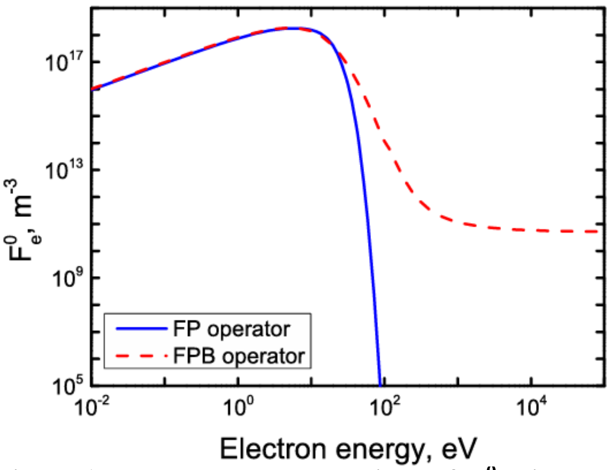

Figure 1. The steady-state solutions of F_e^0 with the Fokker-Planck-Boltzmann (FPB, red dashed curved, h=0.1) and Fokker-Planck (FP, blue solid curve, h=0.99) operators. $n_e = 10^{16}m^{-3}, n_H = 0.99 \times 10^{18}m^{-3}$, and $E = 0.2Vm^{-1}$.

The binary nature of inelastic collisions facilitates electron acceleration in weakly-ionized plasma. This is demonstrated in Fig. 1, where the steady-state solutions are shown. For the demonstration, we only took the test particle part to eliminate RE avalanche effect. The blue curve in Fig. 1 shows the solution where most collisions are described with the FP operator (h=0.99). The resulting $F_e^0 < 10^3\, m^{-3}$ with electron energy above 100 eV. Indeed, no Dreicer flow is expected in such conditions. The red dashed curve shows the solution with the FPB operator (h=0.1). This solution is close to Maxwellian in lower energy where free-free collisions dominate. But it differs significantly at higher energy where binary Boltzmann collisions allow for virtually free acceleration for some particles. These freely accelerated particles become runaways.

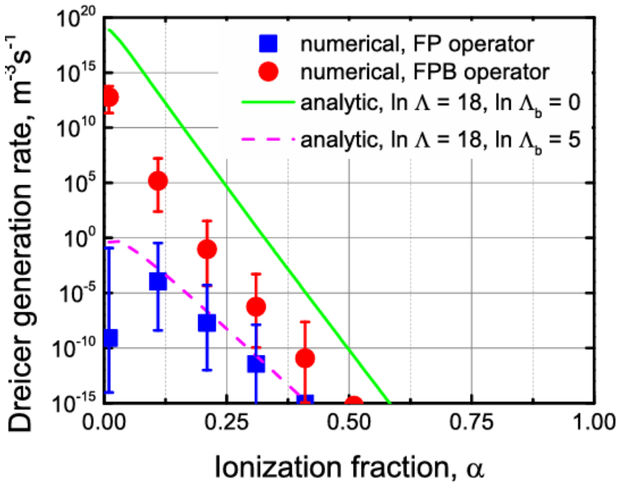

Figure 2. The Dreicer generation rate as a function of α: with FP (blue square, h=0.99) and FPB (red circle, h=0.1) operators. Here, $(n_H + n_e) = 10^{18}m^{-3}, T_e = 5eV$ and $E = 0.2Vm^{-1}$.

Dreicer generation rate as a function of the ionization fraction is shown in Fig. 2. The parameters for this scan correspond roughly to standard Ohmic discharge in KSTAR tokamak and are similar to that of ITER plasma initiation. In this case, a critical role is played by the binary nature of collisions. The Dreicer generation without accounting for the binary nature of collisions is ineffective for these parameters. However, it reaches $10^{13}\ m^{-3}\, s^{-1}$ for $\alpha = 0.01$ in the case of Boltzmann collisions. This is consistent with the analytical Dreicer rates. The observed rates are much lower than the analytic prediction by Connor-Hastie if collisions with bound electrons are ignored in the analytic calculation (green curve in Fig. 2.). We also note that our calculations using FP operator (blue squares) agree with the Connor-Hastie formula with free-bound collisions (dashed curve).

Reference

[1] Lee, Y., Aleynikov, P., De Vries, P. C., Kim, H. T., Lee, J., Hoppe, M., ... & Na, Y. S. (2024). Binary Nature of Collisions Facilitates Runaway Electron Generation in Weakly Ionized Plasmas. *Physical Review Letters*, *133*(17), 175102.