Electron kinetics in AC electric fields: testing the limitations of the HF approximation in the two-term Boltzmann equation

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This work deals with the description of the electron kinetics in plasma discharges excited by AC electric fields. For this purpose, we have carried out a systematic study based on the comparison between two open–source codes recently developed by the N-PRiME team: (i) LoKI-B [1], an electron Boltzmann solver using the classical two-term expansion, and (ii) LoKI - MC [2], a numerical tool that solves the electron kinetics using Monte Carlo techniques. Two-term solvers have been used regularly in plasmas produced by AC electric fields under the *high-frequency (HF) field approximation,* also known as the effective-field approximation, expected to be more reliable when the frequency of the electric field is much larger than the typical frequency for the electron energy relaxation. Having in mind the high accuracy of Monte Carlo models in the description of the electron kinetics in low-temperature plasmas, we have compared the results obtained by LoKI - MC to the ones from LoKI-B for a wide range of discharge parameters, including both the microwave range (1-1000 GHz) and atmospheric pressure, and a radio-frequency of 13.56 MHz and several pressures (0.01 up to 10 Torr). This set of values corresponds to reduced angular frequencies ω/N ranging from ~ $2.6.10^{-16}$ to ~ $2.6.10^{-13}$ rad m^3/s.

Figure 1 shows the results obtained by LoKI-MC and LoKI-B for the mean electron energy and the ionization coefficient in the microwave range (10 and 1000 GHz) in a dry-air discharge. These figures show that for a high-frequency of 1000 GHz the results obtained by LoKI-MC and LoKI-B are quite similar, whereas larger differences between them occur for a lower frequency. This behaviour is easily understood from the inspection of Figure 2, where we compare the field frequency for 10 and 1000 GHz with the characteristic frequency for energy transfer in air at atmospheric pressure. On physical grounds, the isotropic component of the electron energy distribution at 1000 GHz (corresponding to ω/N ~$2.6.10^{-14}$ rad m^3/s) remains practically unchanged during a cycle of the field oscillation and the HF-field approximation can be considered, where only a modulation in the anisotropic component is accounted for. For 10 GHz, this approximation is no longer valid.

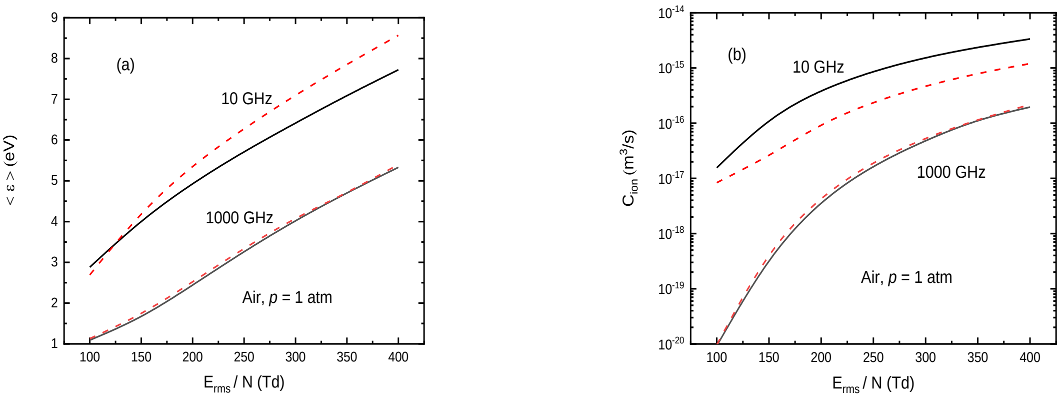

Fig. 1 (a) Mean electron energy and (b) ionization coefficient obtained by LoKI-MC (black curves) and by LoKI-B (dashed red curves) as a function of the root-mean-squared electric field (frequencies of 10 and 1000 GHz) in a dry-air discharge at atmospheric pressure.

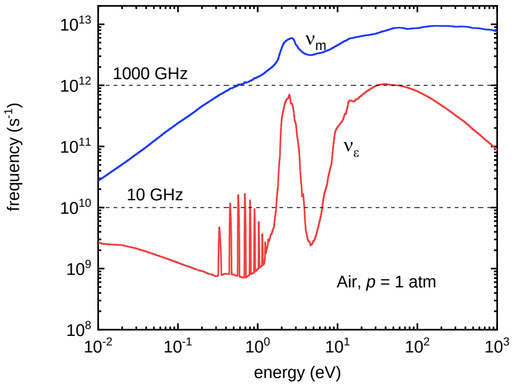

Fig. 2: Energy-dependent frequencies of momentum transfer (blue curves) and energy relaxation (red curves) in air at atmospheric pressure. Horizontal dashed lines indicate frequency values of 10 and 1000 GHz.

Figure 3 reports a similar analysis for Argon, considering lower pressures (0.01 and 1 Torr) and a radio frequency of 13.56 MHz. These results reveal that even for the situation of 0.01 Torr, corresponding to a lower collision frequency, the HF approximation on the two-term Boltzmann equation does not provide accurate results.

The examples shown here clearly exhibit the strong influence of the HF approximation on the results, failing in some cases around an order of magnitude in the ionization coefficient. In the conference, we will discuss in depth the physical reasons for such deviations, and provide advice on the check procedure that modellers should follow before using the HF approximation.

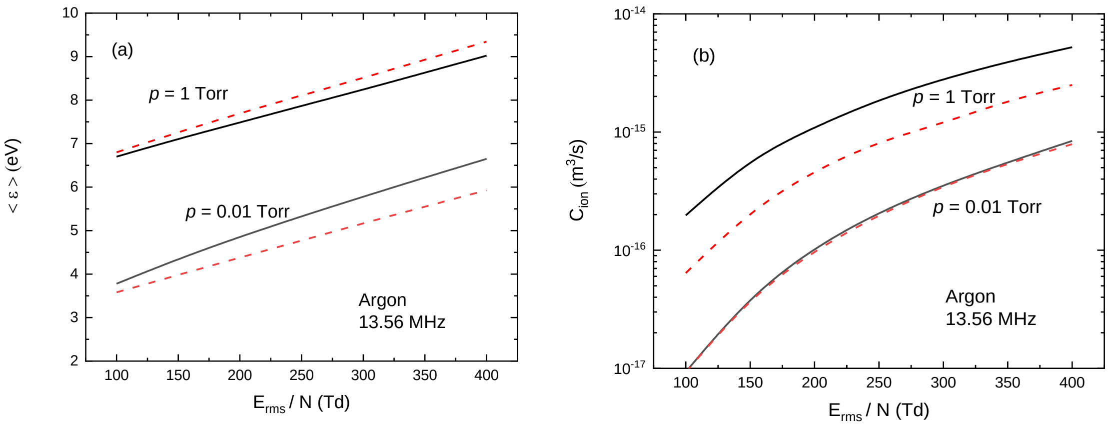

Fig. 3 (a) Mean electron energy and (b) ionization coefficient obtained by LoKI-MC (black curves) and by LoKI-B (dashed red curves) as a function of the root-mean-squared electric field (frequency of 13.56 MHz) in Argon for a pressure of 0.01 and 1 Torr.

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