Benchmarking the Kinetic Global Model framework (KGMf): EEDF evaluations in low-temperature argon plasmas

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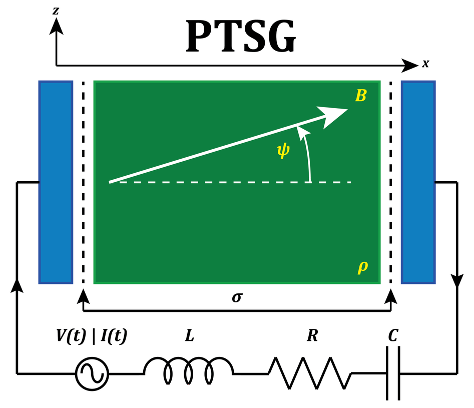

Motivation

The Kinetic Global Model framework (KGMf) presents a valuable and effective tool in predicting macroscopic plasma characteristics in systems involving huge reaction sets, such as plasma assisted combustion [1].

The KGMf with coupled Boltzmann solver

The governing equations for the KGMf: continuity and energy equations.

$$\frac{dn_k}{dt} = \sum_i v_i^k K_i \prod_j n_j + (G-L)_k$$

$$\frac{d}{dt}\left[\frac{3}{2} n_e T_e\right] = \frac{P_{\rm abs}}{V} - n_e \sum_i n_i K_i \Delta E_{ij} + \dot{Q}_e$$

The reaction rate coefficients K_i are computed by:

$$K_i(f,t) = \sqrt{\frac{2e}{m_e}} \int_0^\infty \sigma_i(\varepsilon)\varepsilon f(\varepsilon,t) d\varepsilon$$

where $f(\varepsilon, t)$ is the electron energy distribution function (EEDF) and $\sigma(\varepsilon)$ is the reaction cross section [2].

The KGMf is coupled with a Boltzmann equation (BE) solver BOLOS [3] to self-consistently compute the EEDF.

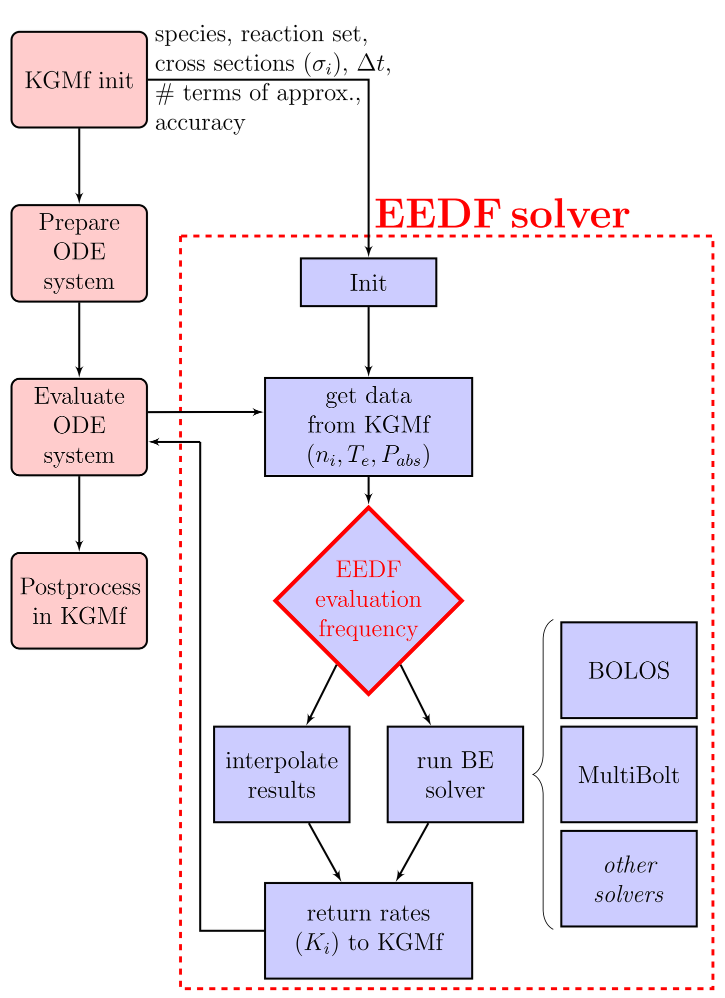

Figure 1. Coupling KGMf with BE solver.

Benchmark with ZDPlasKin

Electron mobility (μ_e) and electron temperature (T_e) were computed from EEDF by using the coupled BE solver. The temporal evolution of species densities and reaction rates are compared.

Table 1. Reaction set for argon.

R1: $Ar + e \rightarrow Ar^+ + 2e$
R2: $Ar + e \rightarrow Ar^* + e$
R3: $Ar^* + e \rightarrow Ar^+ + 2e$
R4: $Ar_2^+ + e \rightarrow Ar^* + Ar$
R5: $Ar_2^+ + Ar \rightarrow Ar^+ + 2Ar$
R6: $Ar^* + Ar^* \rightarrow Ar_2^+ + e$
R7: $Ar^+ + 2e \rightarrow Ar + e$
R8: $Ar^* + 2Ar \rightarrow Ar + 2Ar$
R9: $Ar^+ + 2Ar \rightarrow Ar_2^+ + Ar$

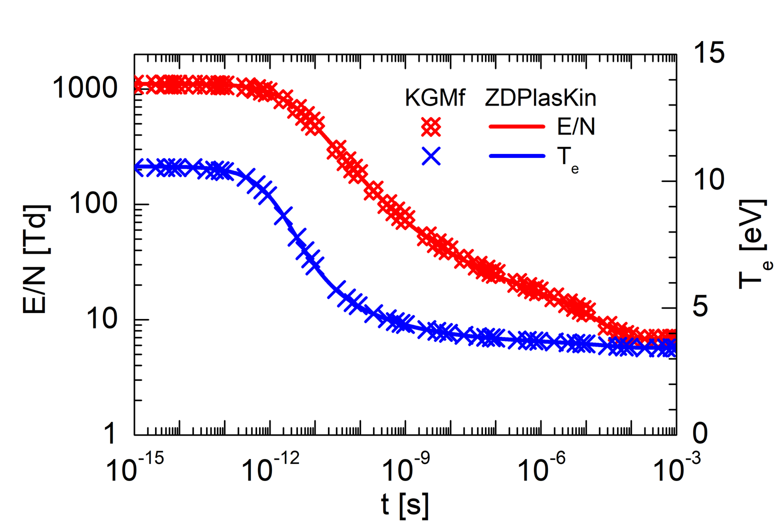

Figure 2. Temporal evolution of E/N and T_e.

ZDPlasKin was coupled with BOLSIG+ [4]. Both BE solvers are using two-term spherical approximation of the Boltzmann equation.

$$\left(\frac{E}{N}\right) = \frac{1}{N}\left(\frac{\tilde{P}}{n_e\, e\, \mu_e}\right)^{1/2} \qquad T_e = \frac{2}{3}\int_0^\infty \varepsilon f(\varepsilon) d\varepsilon$$

Simulation Results

The KGMf was benchmarked with ZDPlasKin in atmospheric pressure low-temperature argon plasmas. The Ohmic heating of electrons ($\tilde{P}_{\rm abs} = e\mu_e n_e E^2$) and user defined absorbed power are implemented.

▷ Temporal EEDF evaluations

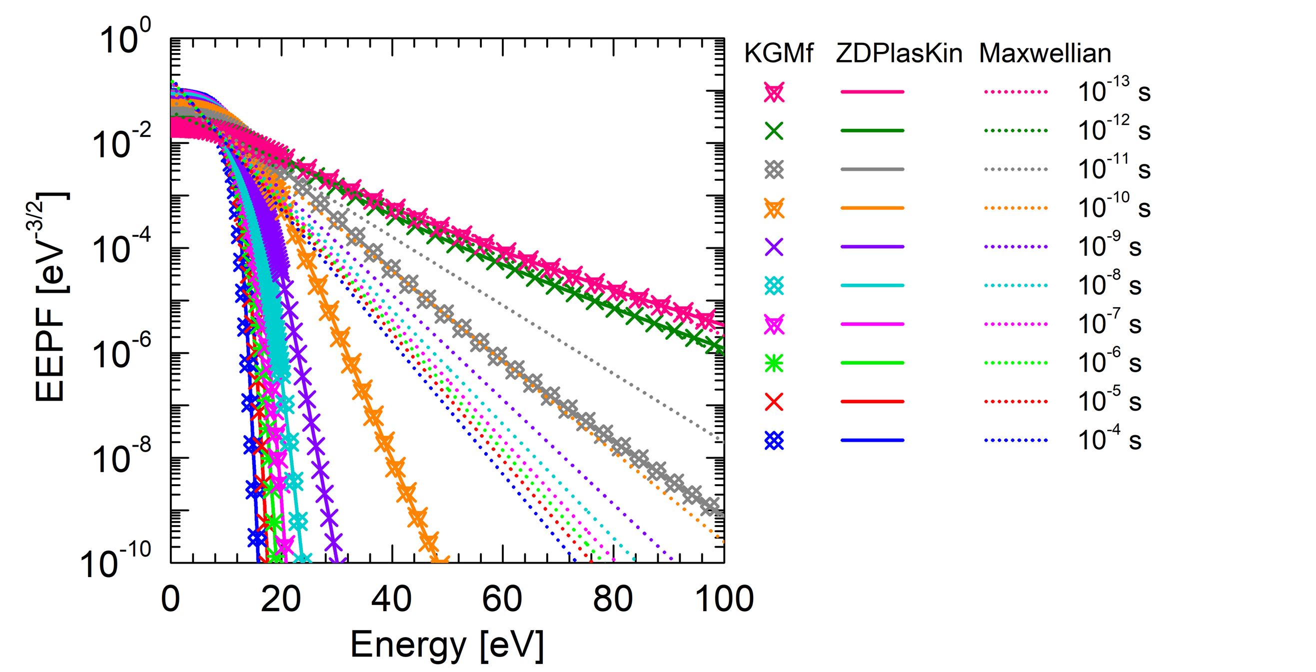

Figure 3. Temporal evolution of the EEDF from coupled BE solvers.

▷ Temporal evolutions

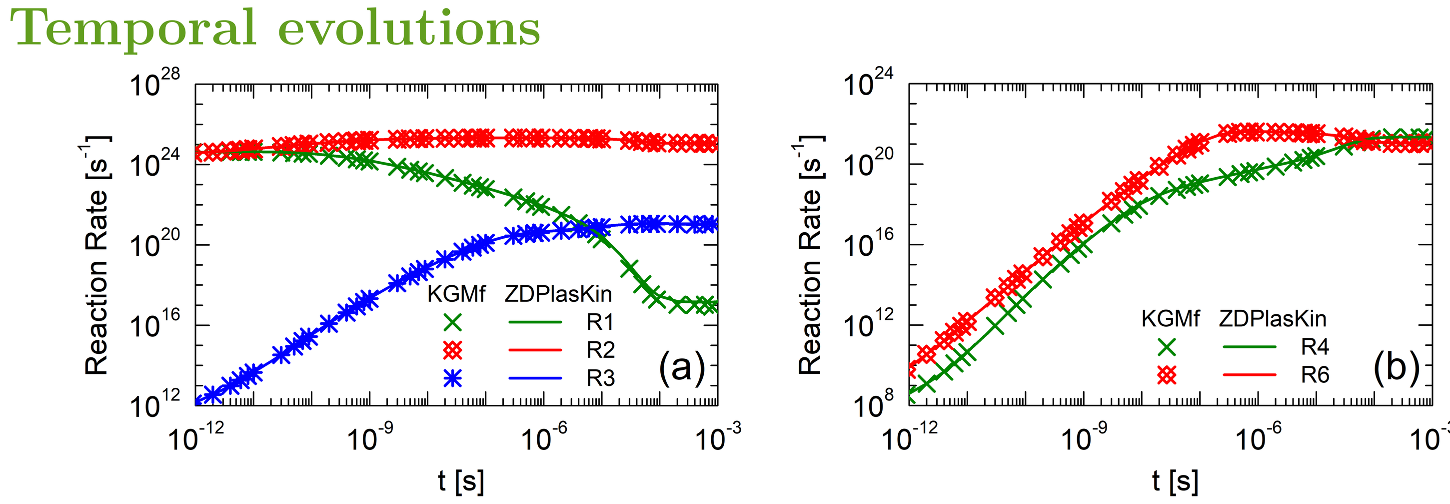

Figure 4. Temporal evolution of reaction rates with $\tilde{P}_{\rm abs} = 50$ W/cm^3.

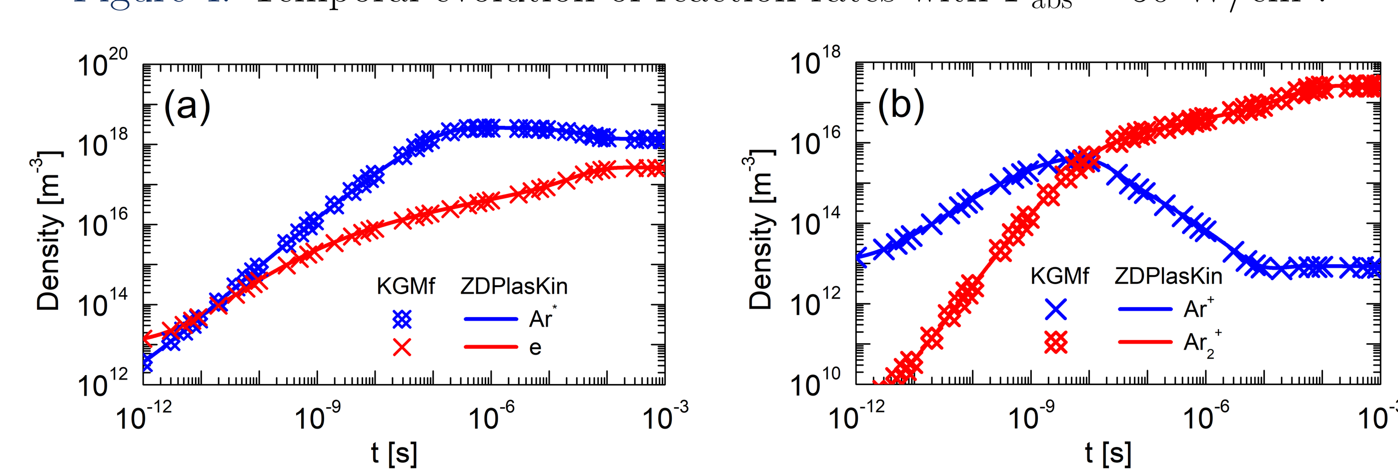

Figure 5. Temporal evolution of densities with $\tilde{P}_{\rm abs} = 50$ W/cm^3.

▷ Steady-state densities

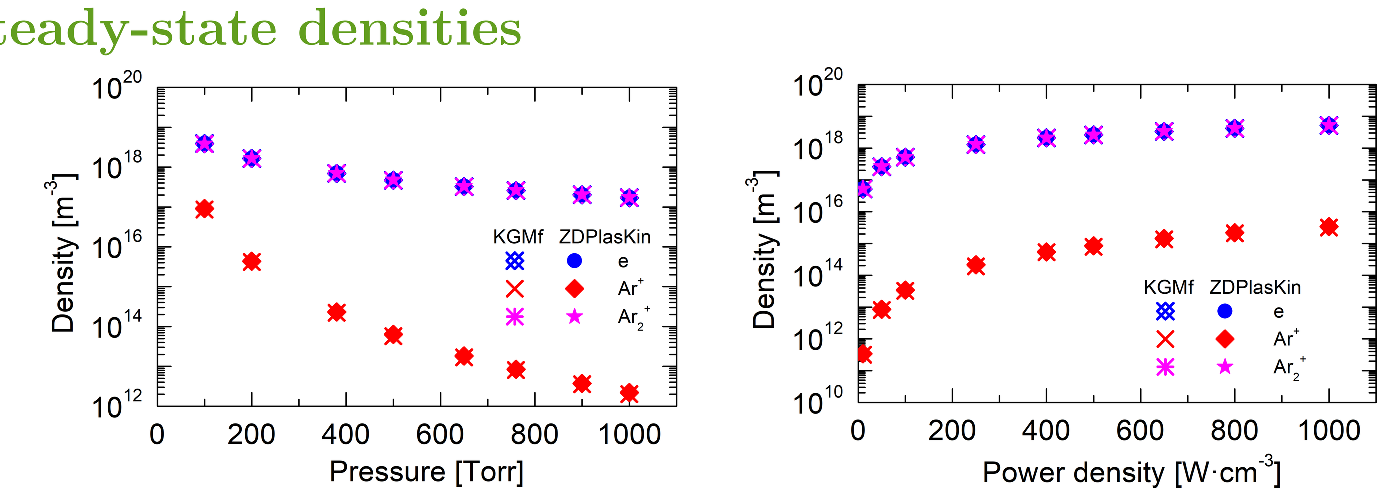

Figure 6. Steady-state densities for range of pressures with $P_{\rm abs} = 50$ W/cm^3 (left) and range of input powers with $p = 760$ Torr (right).

Application to Microwave Breakdown

The KGMf with coupled BE solver can be applied to various plasma discharge systems. Here we present the application to high power microwave (HPM) breakdown [5]. Argon is a working gas and the simulation parameters are: $E_0 = 2.82$ MV/m, $\omega = 2.85$ GHz, and $n_{e,init} = 10^{13}$ m^{-3}. Breakdown time is time when the electron density reaches 10^8 times the initial density.

Effective microwave field and absorbed power are computed using equations below:

$$E_{\rm eff} = \frac{E_0}{\sqrt{2}} \frac{\nu_m}{\sqrt{\nu_m^2 + \omega^2}} \qquad P_{\rm abs} = \int_0^\infty \frac{e^2 n_e}{m_e \nu_m} E_{\rm eff}^2 f(\varepsilon) d\varepsilon$$

where f is the EEDF and ν_m is the moment transfer collision frequency.

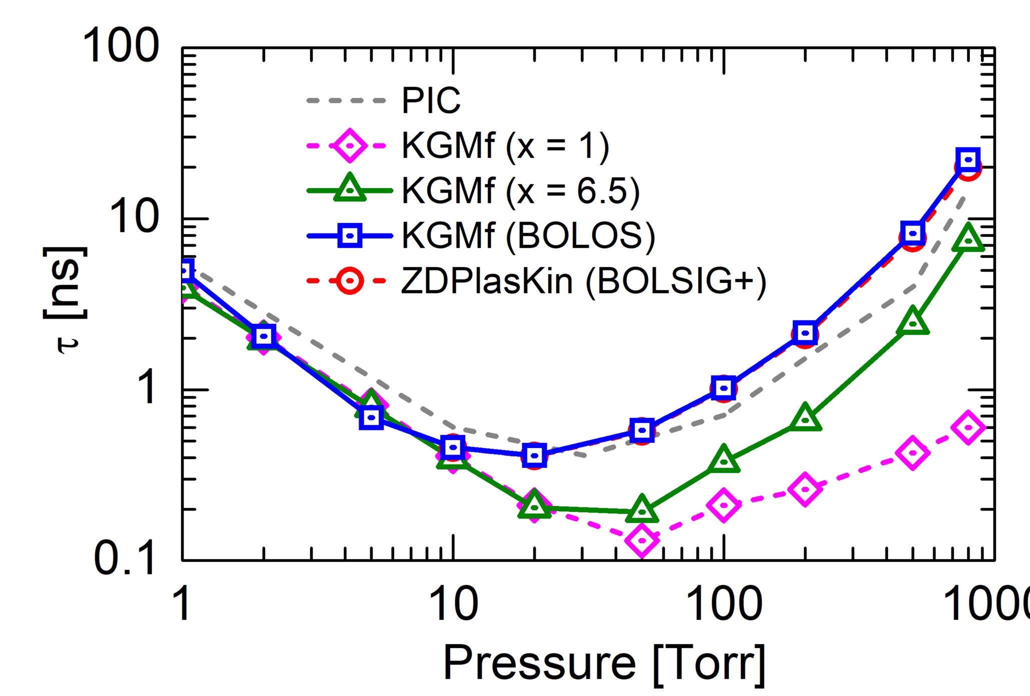

Figure 7. Breakdown times at different pressures in HPM breakdown.

Conclusions

- The KGMf is coupled with a BE solver (BOLOS) to self-consistently evaluate temporal evolution of the EEDF.
- The results of the KGMf are benchmarked with ZDPlasKin, showing good agreement both during the transient and at the steady state.
- The application of the KGMf to the HPM breakdown is presented.
- Applications of the KGMf to more complex plasma discharge systems, e.g., plasma assisted combustion, will be further explored.

Acknowledgment

Work is supported by DOE Plasma Science Center grant DE-SC0001939.

References

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