Calculations of Ionization Time-scales in a Laser-irradiated Plasma

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Introduction

- Many models assume Local Thermodynamic Equilibrium (LTE) – ionization levels determined by Saha-Boltzmann equation.
- Collisional-radiative model has been used to determine the time for LTE to be established.
- Relevant to recent studies of EUV laser hole-drilling.

Model

- Zero dimensional plasma.
- Electronic and photonic processes:

$$K_i^{\uparrow} = 3\times10^{-6}\xi T_e^{-1/2}\frac{E_1(E_i/T_e)}{E_i} \quad J_j^{\uparrow} = 1\times10^{-13}A_j T_e^{-1/2}\frac{E_1(E_j/T_e)}{(E_j)^3}$$

$$K_i^{\downarrow} = \frac{1}{2}\left(\frac{2\pi(\hbar c)^2}{m_e c^2 T_e}\right)^{\frac{3}{2}}\frac{g_{i+1}}{g_i}\exp\left(-\frac{\Delta E_i}{T_e}\right)K_i^{\uparrow} \quad J_j^{\downarrow} = \frac{g_{j+1}}{g_j}\exp\left(-\frac{E_j}{T_e}\right)J_j^{\uparrow}$$

- Self consistent electron temperature:

$$\varepsilon_{kin} = \frac{3}{2}n_e T_e$$

- Continuum lowering (Stewart-Pyatt):

$$\Delta E = \frac{1}{2(Z^*+1)}\left[\left(\frac{3(Z^*+1)Ze^3 n_e^{1/2}}{4\pi\epsilon_0^{3/2}} + T_e^{3/2}\right)^{\frac{2}{3}} - T_e\right]$$

- Ions and electrons have velocity distributions (verified by Spitzer formula):

$$f(v) = f_{Maxwellian}(T_e) \qquad T_i = 0$$

- Time dependence solved by regular RK-4 algorithm.

Hydrogen: Analytical Comparison

- Possible to derive an analytic expression to confirm the algorithm:

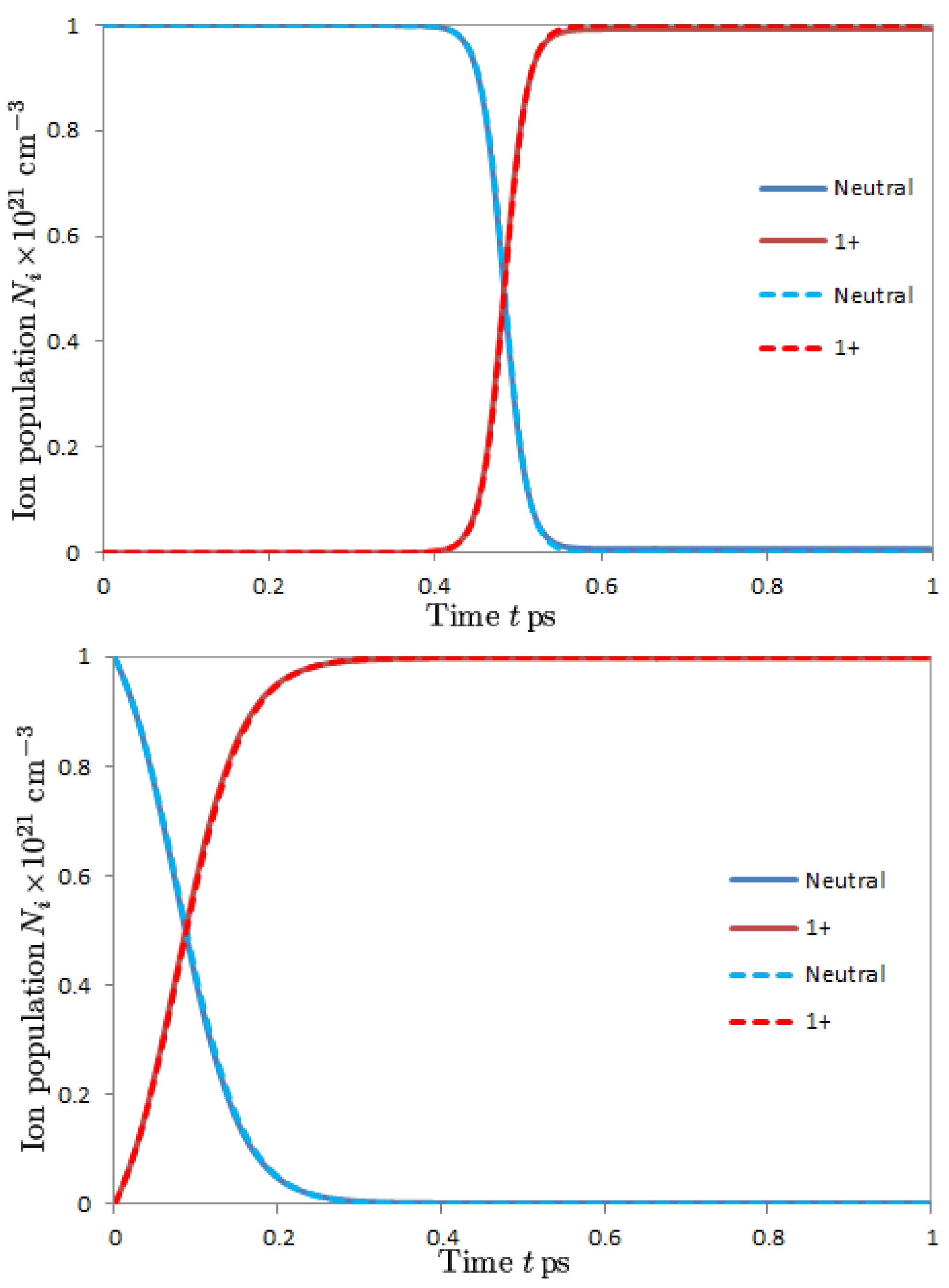

Figure 1: Comparison of computational results (dashed) with analytical solution (solid) for Hydrogen. (a) Collisional processes only at constant temperature (25eV) (b) similar situation with photoionization.

Carbon: Ionization from Solid

- Incident radiation photoionizes electrons and injects energy into the system.
- Electron temperature drops initially and begins to recover as Inverse Bremsstrahlung absorption increases.

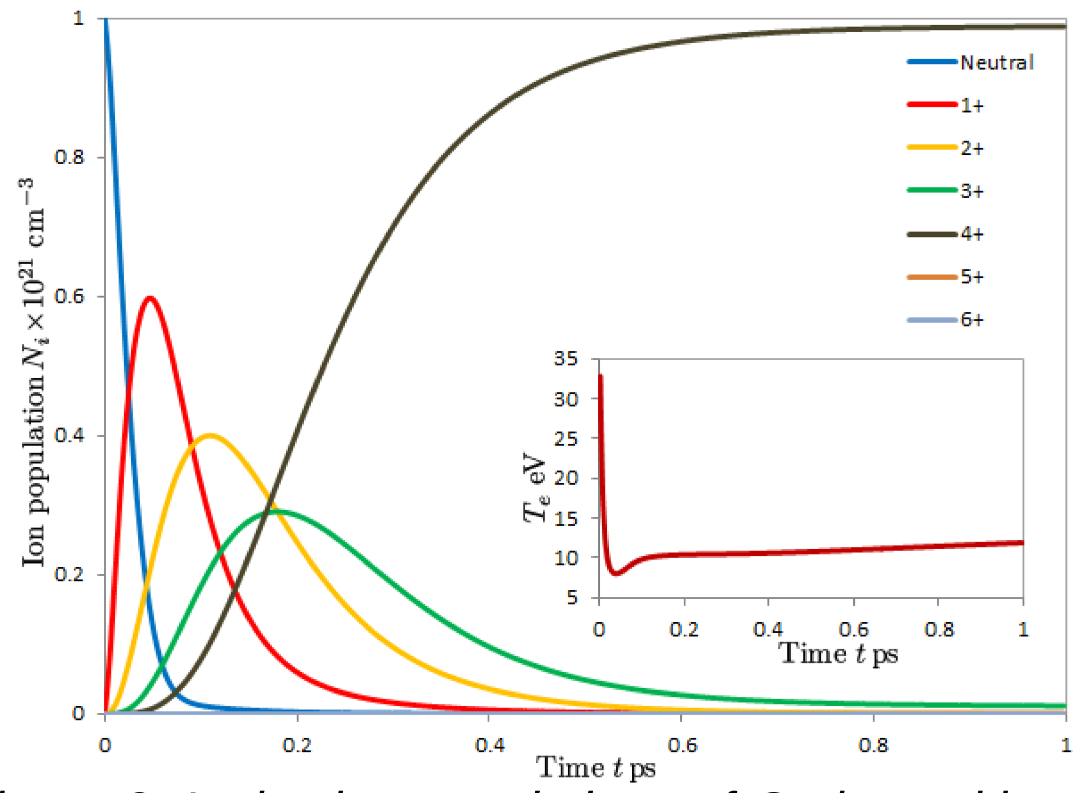

Figure 2: Ionization populations of Carbon with an incident EUV beam. Inset: corresponding electron temperature plot.

Energy Deposition Scenarios

- Simulation of system where energy is injected to raise electron temperature from cold (25eV) to hot (100-1000eV).
- Energy is raised by linear coupling to electrons or via photoabsorption.

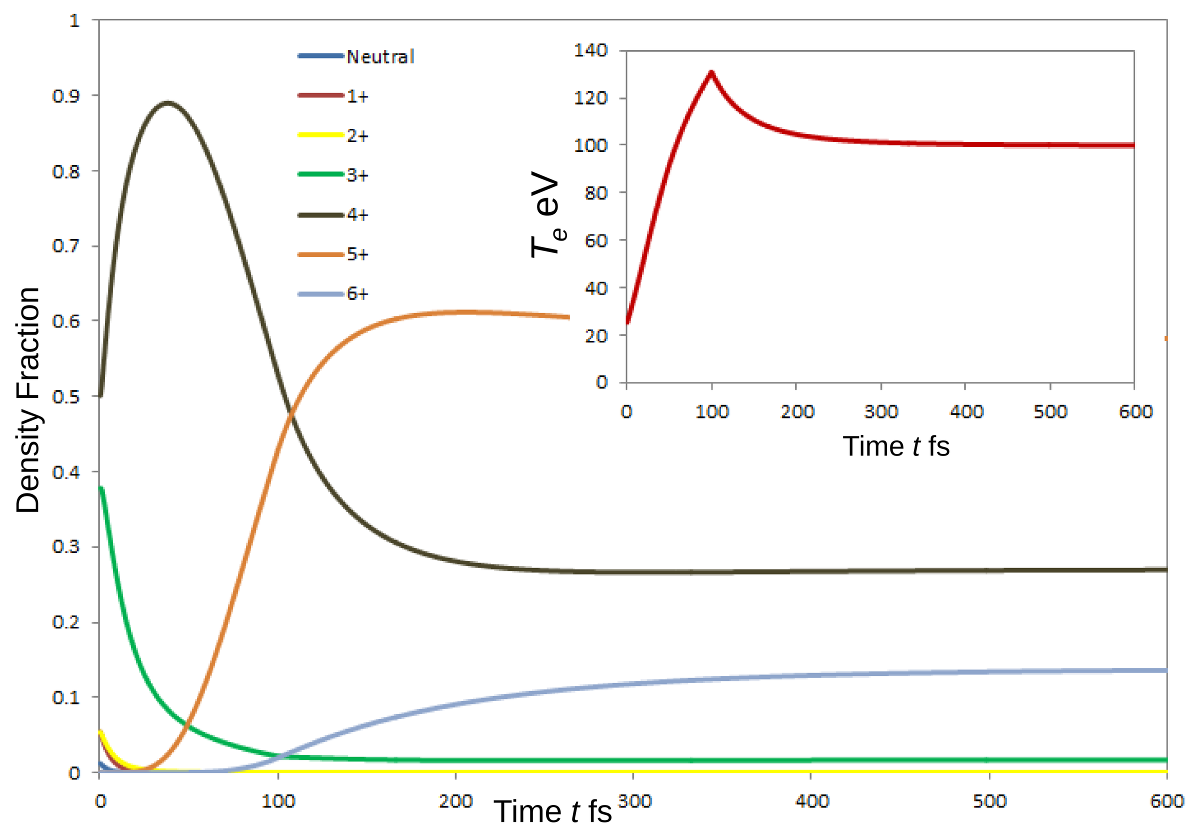

Figure 3: Ionization populations for a linear energy deposition into Carbon from 25eV to 100eV. Inset: corresponding electron temperature plot.

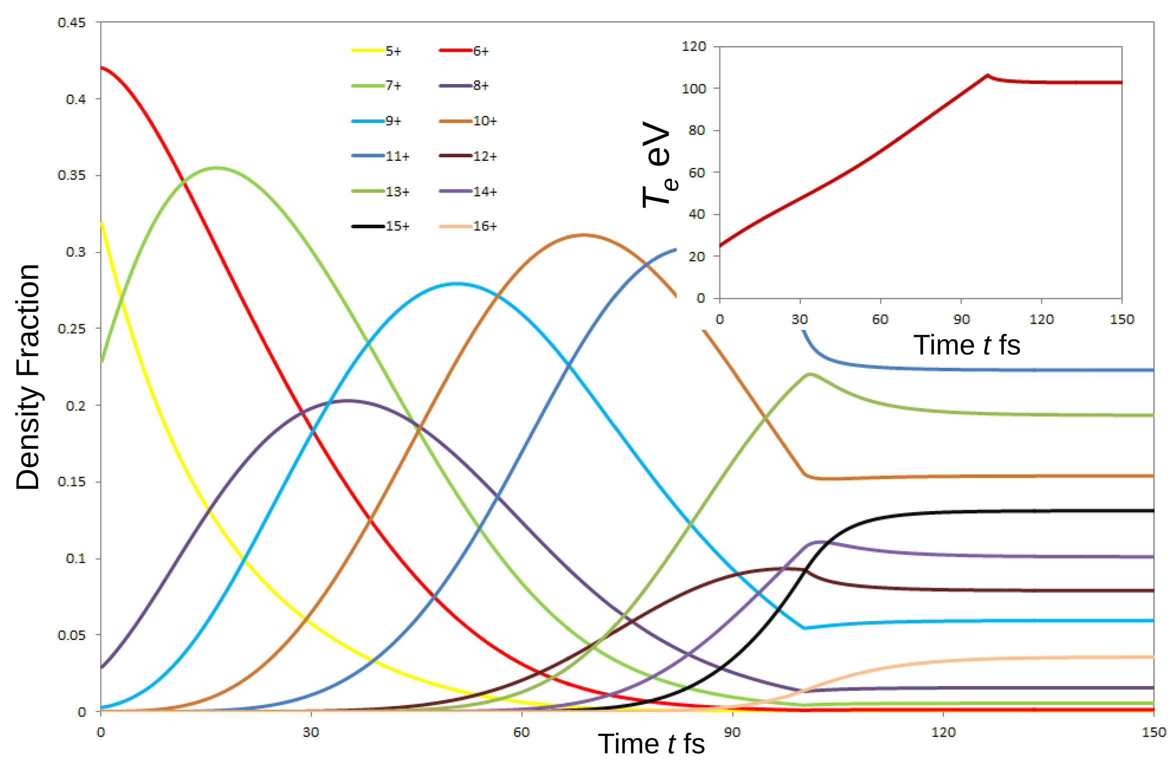

Figure 4: Ionization populations for photonic energy deposition into Iron from 25eV to ~100eV. Inset: corresponding electron temperature plot.

Density-dependent Timescales

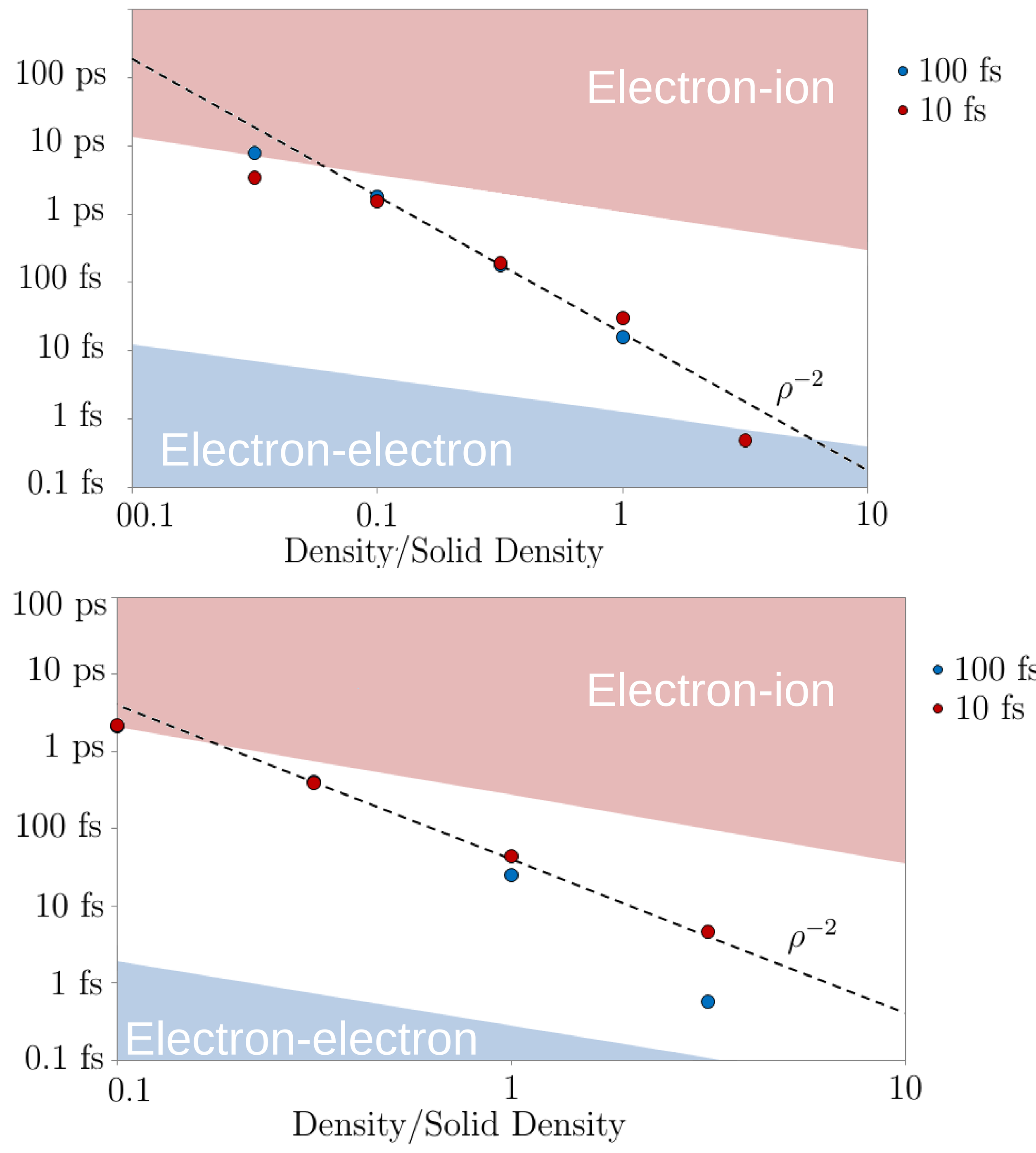

Figure 5: Equilibration times as a function of ion density for (a) Iron and (b) Carbon, in the case of linear energy deposition. Energy was deposited to raise the temperature from 25eV to 100eV. Two different deposition times are shown. The validity regions, where electrons assume a Maxwellian and ions remain stationary, are given by the appropriate Spitzer formulas.

Conclusions

- The assumption of LTE is valid for many hydrodynamic processes.
- Processes on timescales longer than of order femtoseconds do not require a full rate treatment to accurately model population levels.
- Equilibration times have a quadratic dependence on ion density.

Future Work

- The effects of a super-Gaussian electron distribution on equilibrium populations in the presence of non-thermal radiation is relevant to current ICF experiments.
- Scenarios with different incident radiation are being explored.

References

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