THERMOS Toolkit: taking into account non-equilibrium plasma effects in RHD calculations

A.S. Grushin[1], I.Yu. Vichev[1], A.D. Solomyannaya[1], D.A. Kim[1,2], I.P. Tsygvintsev[1]

[1]Keldysh Institute of Applied Mathematics, Moscow, Russia; [2]National Research Nuclear University MEPhI

Introduction

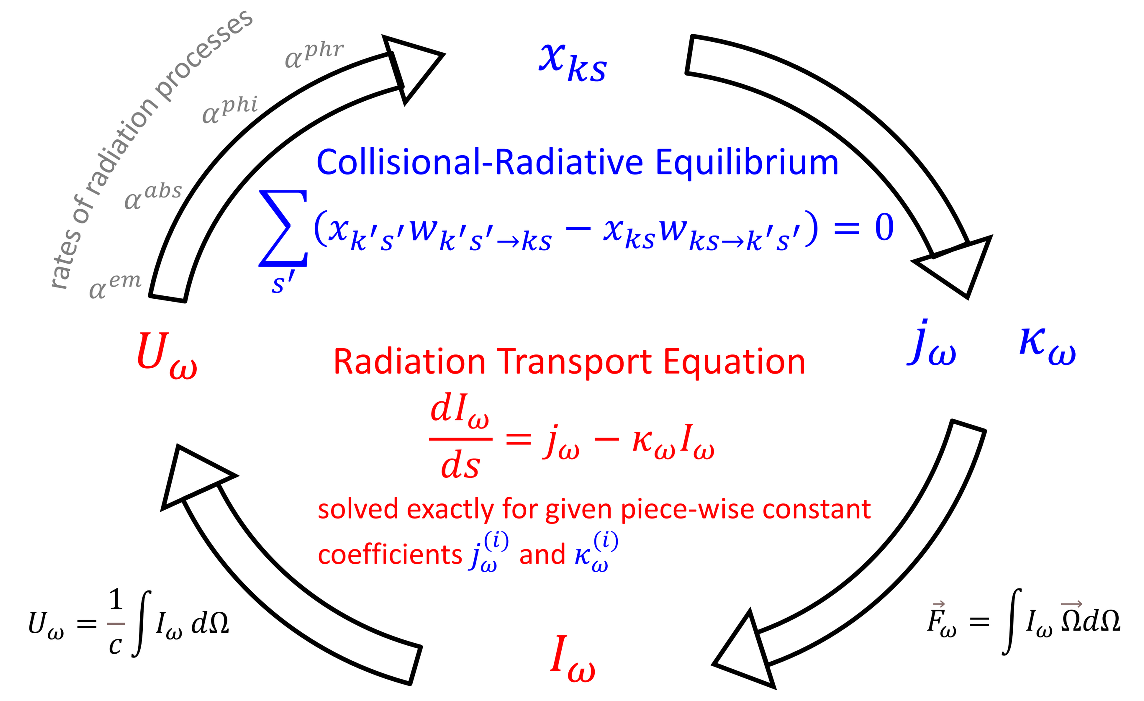
In typical laboratory plasma (LPP, z-pinch) its key characteristic – states population – is mostly defined by radiation field and collisional processes. The latter factor can be considered local for the majority of typical cases and effectively described by temperature. The radiation field on the other hand is not a local characteristic but defined by plasma surroundings. Taking it correctly into account in RHD simulation is important in order to obtain plausible results especially at pre-expansion stage.

Though most of the practical plasma dynamics simulations are still run at the expense of accurate atomic physics calculations in favor for hydrodynamics. A widespread approach is to use one the most suitable for the task at hand approximation for opacity and EOS calculations, i.e. LTE or transparent plasma.

In this report we consider various approaches to this problem and outline their areas of applicability:

- Single approximation (LTE, transparent plasma, partial Planckian);
- Escape-factor interpolation [1] between two limiting radiation field approximations, i.e. LTE and transparent plasma;
- Multi-Planckian approach;
- Self-consistent solution of the radiation transport equation with kinetics [2].

Self-consistent solution of the RTE with kinetics



Escape-factor interpolation

Based on the assumption, that local radiation field varies between two limiting cases one can introduce quantitative escape-factor

$$\xi = \int_0^\infty U_\omega(\omega)d\omega \Big/ \int_0^\infty U_\omega^1(\omega)d\omega$$

where U_ω is the solution of radiation transport equation, U_ω^1 – spectral energy density for optically thick case. Once the ξ is calculated, plasma characteristics are obtained via relation

$$f = f^0 \times (1-\xi) + f^1 \times \xi,$$

where f – mean charge, mass absorption coefficient, etc.; index 0 corresponds to optically thin case and index 1 – optically thick case.

Multi-Planckian approach

Out of three temperatures $T_i = T_e$, T_r is considered independent, additionally the dilution factor α is introduced to take into account the finiteness of plasma. Thus the spectral density of energy for radiation field:

$$U_\omega^P(\omega, T_r, \alpha) = \frac{4\pi}{c}\frac{15}{\pi^5}\sigma\omega^3 \frac{\alpha}{\exp(\omega/T_r)-1}.$$

In RHD simulation the local dilution factor $\tilde{\alpha}$ is defined as

$$\tilde{\alpha} = \frac{\int_0^\infty U_\omega(\omega)d\omega}{\int_0^\infty U_\omega^P(\omega, \tilde{T}_r, \alpha')\big|_{\alpha'=1} d\omega},$$

where U_ω is the solution of radiation transport equation for current cell, $\tilde{T}_r$ – local radiation temperature, determined, for example, minimization of $\|U_\omega(\omega) - U_\omega^P(\omega, \tilde{T}_r, \tilde{\alpha})\|_{L^2}$.

For an RHD simulation 4-dimensional set of tables is prepared, covering ranges over density ρ, electron temperature T_e, radiation temperature T_r and dilution factor α. Appropriate interpolation is used for local $(\tilde{\rho}, \tilde{T}_e, \tilde{T}_r, \tilde{\alpha})$.

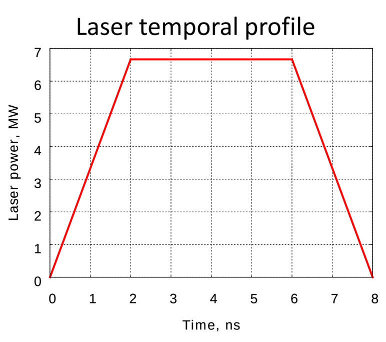
Simulation task #1

Aluminum bulk target

Nd:YAG laser (λ = 1.06 µm), focal spot ⌀76 µm, incident angle 45°, E_{Las} = 40 mJ, I_{MAX} ≈ 0.35 TW/cm^2.

2D (r, z) RHD simulation [3] provides density and temperature profiles (r = 0).

RTE is then solved in 1D flat layer geometry.



Plot designations:

Cons. sim. – self-consistent solution of the RTE with kinetics;

Multi-Planckian – multi-Planckian approach;

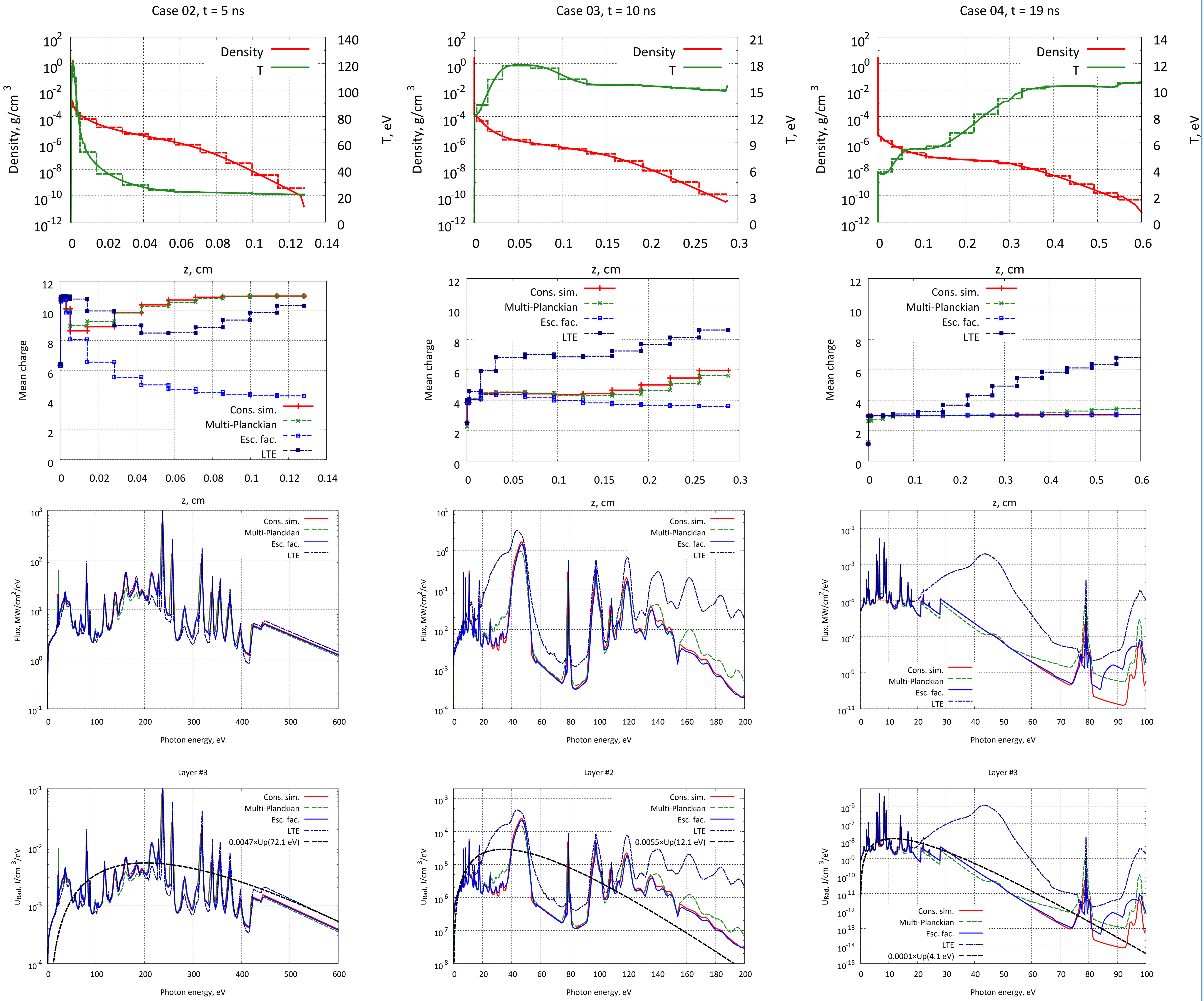
Esc. fac. – escape-factor interpolation (in these cases between LTE and transparent plasma approximation);

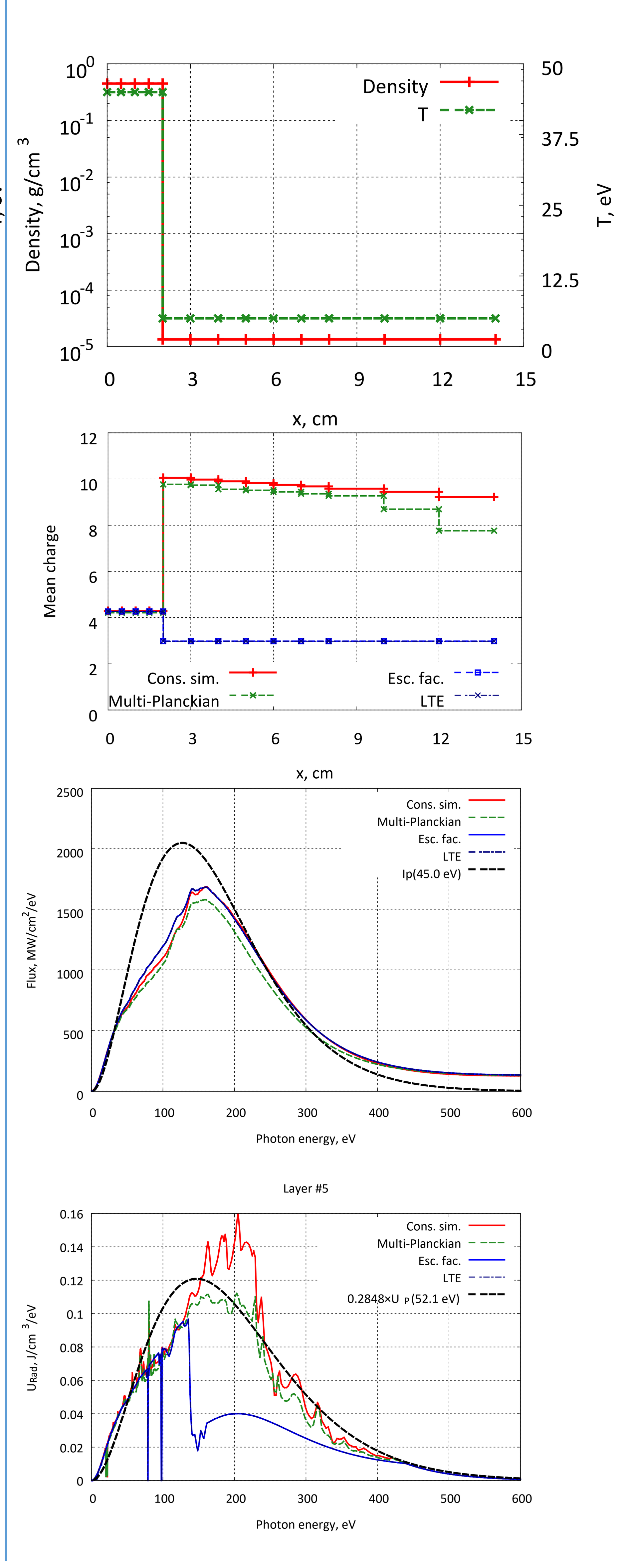
LTE – single approximation, LTE.

Simulation task #2

Aluminum plasma, 1D flat geometry.

Photoionization of outer rarefied layers by thermal radiation of inner hot dense plasma core.





In all of these calculations the transparent plasma approximation produced results almost identical to those of the escape-factor interpolation and has been omitted from the plots to preserve clarity.

Conclusions

- As one can see from the figures, the local radiation field in these cases is far from Planckian form both qualitatively and quantitatively. And in order to obtain adequate results RHD simulation this fact needs to be accounted for.
- The Multi-Planckian approach seems to be the closest one to the self-consistent solution – it produces low discrepancy for the mean charge and acceptable deviations in spectral features.
- The escape-factor interpolation provides reasonable fluxes, but generally fails to reproduce mean charge of the plasma. The reasons behind this require more thorough analysis.
- Single LTE approximation seems to be the most inapplicable for the selected simulation cases, although the single transparent plasma approximation showed results almost identical to the escape-factor method.

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References:

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