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THERMOS Toolkit:
self-consistent solution of the radiation transfer equation in 1D geometries with kinetics

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

[1]Keldysh Institute of Applied Mathematics, Miusskaya sq. 4, Moscow 125047,Russia
[2]National Research Nuclear University MEPhI, 31 Kashirskoe Highway, Moscow 115409, Russia

vichevilya@keldysh.ru

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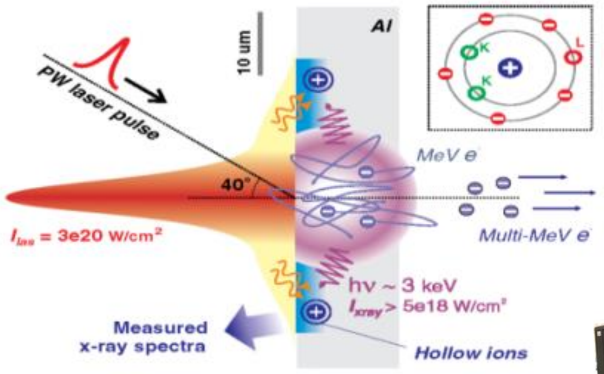
Calculations have been performed at HPC K-100 (KIAM RAS) and MVS-10P (JSCC RAS).

Introduction

SIMULATION

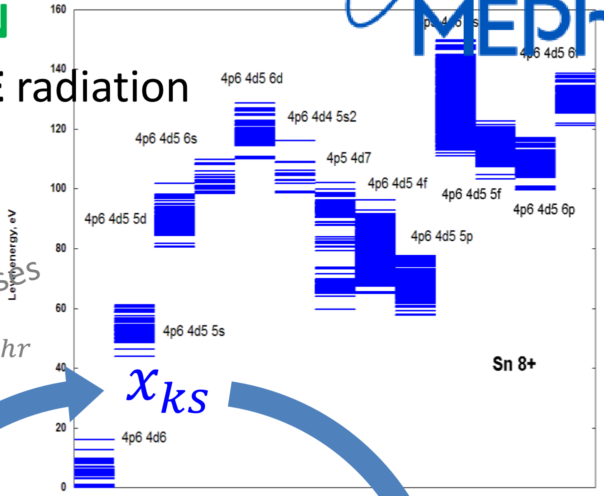
plasma dynamics with **Non-LTE** radiation

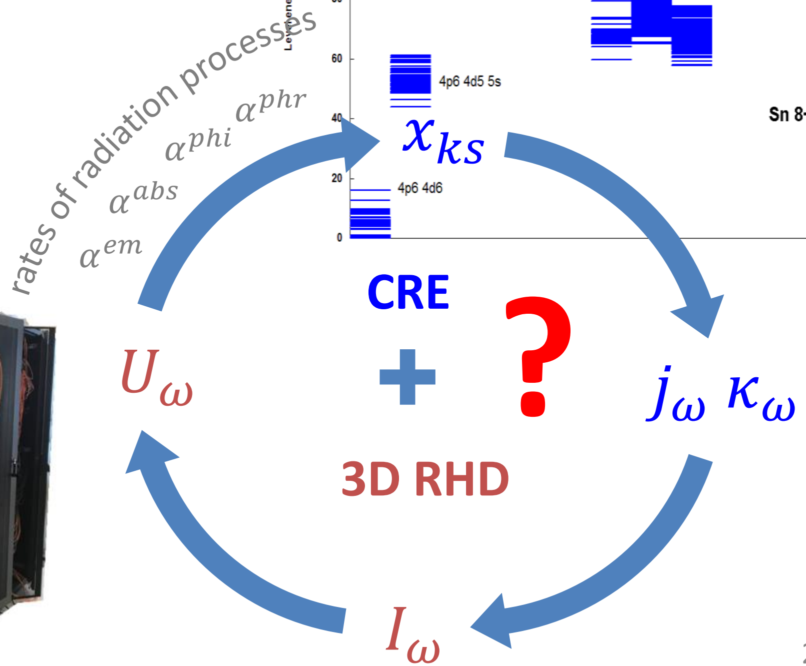
EXPERIMENT



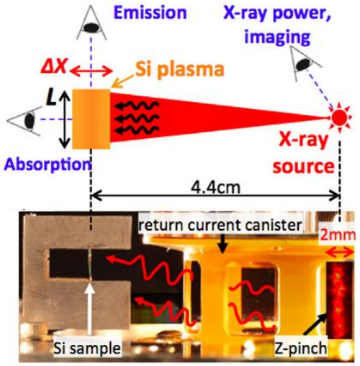
Kinetics up to 10^6 states

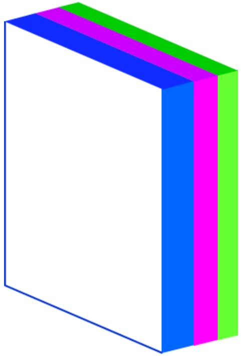
HPC



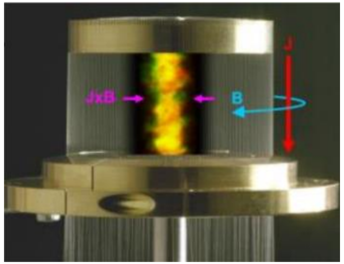


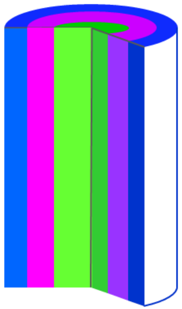
Plasma formations ⇒ 1D geometries



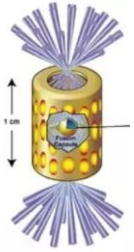


infinite flat

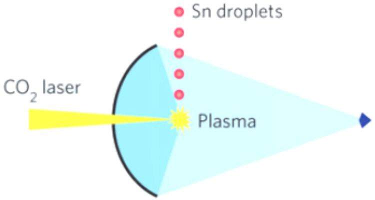


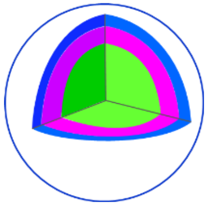


infinite cylinder



Laser-produced plasma





ball

Self-consistent solution of the RTE with kinetics

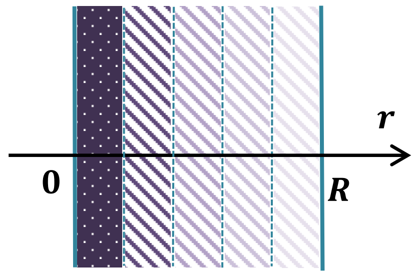
Collisional-Radiative Equilibrium

$$\sum_{s'} \left(x_{k's'} w_{k's' \to ks} - x_{ks} w_{ks \to k's'} \right) = 0$$

$\delta Q < \delta \varepsilon$

radiative losses

$$Q = 4\pi \int j_\omega d\omega$$



$\{r = [0, R] : r_{i-1} < r < r_i, i = 1, N\}$

$\Delta r = r_i - r_{i-1}$

$T_e^{(i)}$ – electron temperature

$n_i^{(i)}$ – ion density

Radiation Transport Equation

$$\frac{dI_\omega}{ds} = j_\omega - \kappa_\omega I_\omega$$

solved exactly for given piece-wise constant coefficients $j_\omega^{(i)}$ and $\varkappa_\omega^{(i)}$

$$U_\omega = \frac{1}{c} \int I_\omega \, d\Omega$$

$$\vec{F}_\omega = \int I_\omega \, \vec{\Omega} d\Omega$$

k is ionization degree
s is quantum state
$x_{ks}(U_\omega)$ is populations
$w_{ks \to k's'}(U_\omega)$ is total probability
$j_\omega(x_{ks})$ is emissivity
$\kappa_\omega(x_{ks})$ is opacity
$I_\omega(j_\omega, \kappa_\omega)$ is radiation intensity
$U_\omega(I_\omega)$ is radiation energy density
$F_\omega(I_\omega)$ is radiation energy flux

Reference:
THERMOS: Consistent solution of the radiation transport equation with level kinetics in simple geometries / I.Yu.Vichev [et al.] // Keldysh Institute Preprints. 2020. № 56. 30 p. http://doi.org/10.20948/prepr-2020-56 URL: http://library.keldysh.ru/preprint.asp?id=2020-56 (in Russian)
Vichev, I.Y., Solomyannaya, A.D., Grushin, A.S., Kim, D.A. (2019). On certain aspects of the THERMOS toolkit for modeling experiments. *High Energy Density Physics*, 100713. https://doi.org/10.1016/J.HEDP.2019.100713

Spectral radiation energy flux in limiting cases

	optically thin $\tau \ll 1$	optically thick $\tau \gg 1$
flat	$F_\omega = 2\pi \sum_{i=1}^{N} j_\omega^{(i)} (r_i - r_{i-1})$	$\tau = \kappa \Delta r$ – optical depth
cylinder	$F_\omega = 2\pi \frac{1}{R} \sum_{i=1}^{N} j_\omega^{(i)} (r_i^2 - r_{i-1}^2)$	$F_\omega = \pi \left. \frac{j_\omega{}^{(i)}}{\kappa_\omega{}^{(i)}} \right\rvert_{i=N} = \pi B_\omega \left(T_e^{(i=N)} \right)$
ball	$F_\omega = \frac{4\pi}{3} \frac{1}{R^2} \sum_{i=1}^{N} j_\omega^{(i)} (r_i^3 - r_{i-1}^3)$	

$$\forall i: \frac{j_\omega{}^{(i)}}{\kappa_\omega{}^{(i)}} = B_\omega \left(T_e^{(i)} \right),\ B_\omega(T) = \frac{15\sigma}{\pi^5} \frac{\omega^3}{e^{\omega/T} - 1}$$

Problem statement for program verification

$$\{r = [0, R] : r_{i-1} < r < r_i, i = 1, N\}$$

$$\Delta r = r_i - r_{i-1}$$

Si plasma

$N = 5$

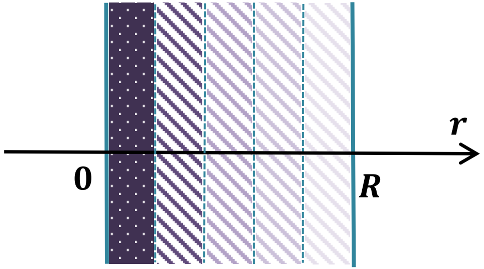
$T_1 = 100$ eV

$T_2 = 70$ eV

$T_3 = 60$ eV

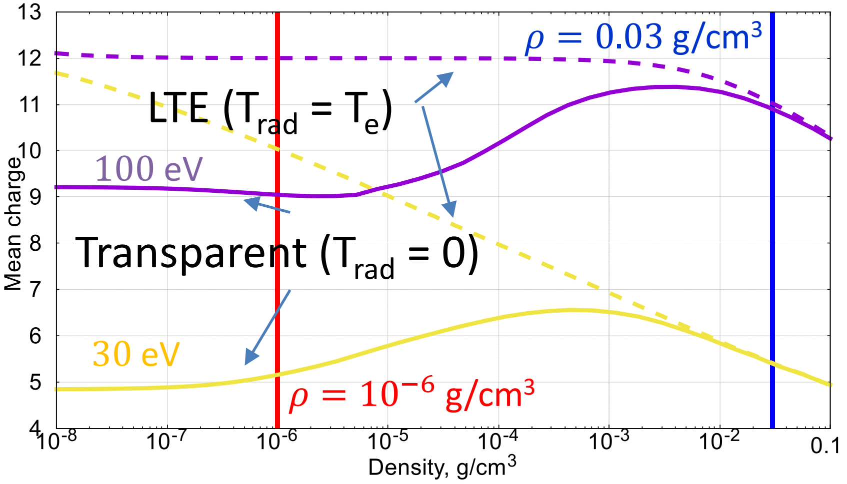
$T_4 = 40$ eV

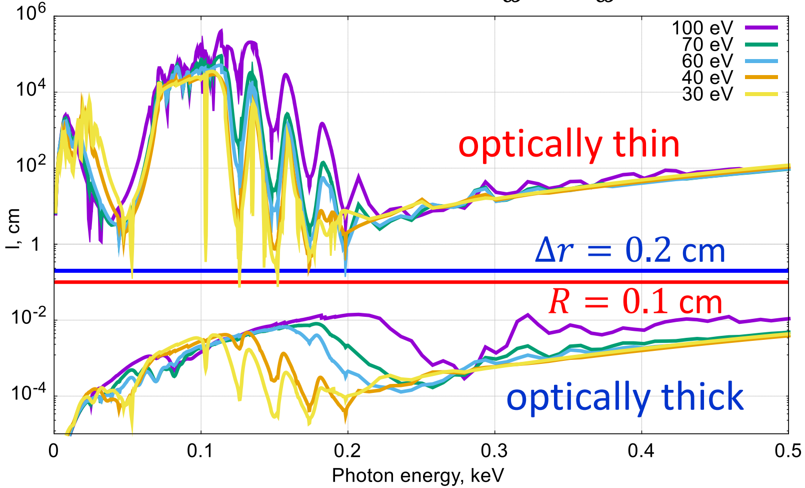
$T_5 = 30$ eV



optically thin $\tau \ll 1$	optically thick $\tau \gg 1$
$\rho = 10^{-6}$ g/cm³	$\rho = 0.03$ g/cm³
$\Delta r = 0.02$ cm, $R = 0.1$ cm	$\Delta r = 0.2$ cm, $R = 1$ cm
$\forall \omega : R < l_\omega$	$\forall \omega : \Delta r > l_\omega$

$l_\omega = \kappa_\omega^{-1}$



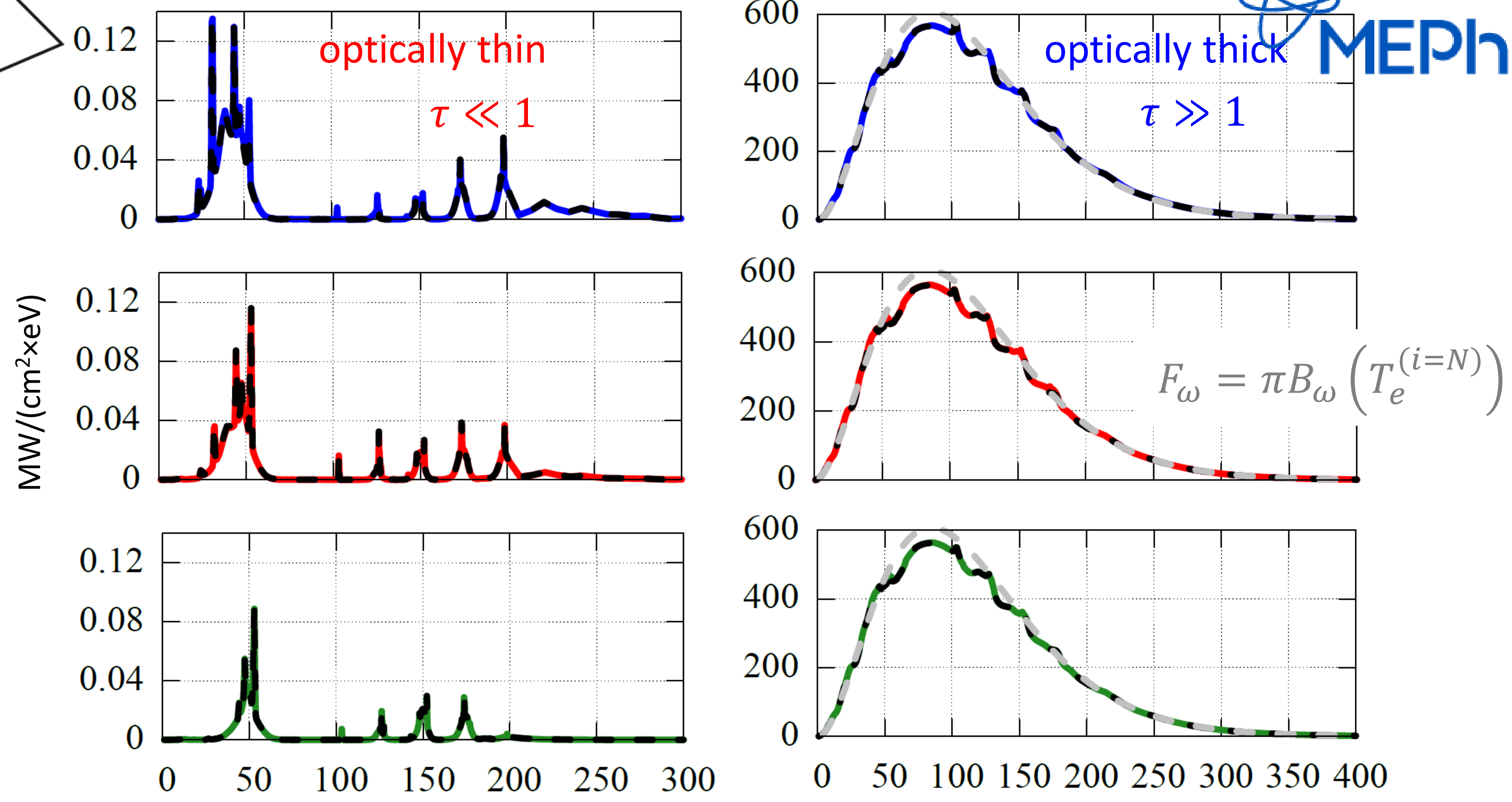


Calculation results of spectral radiation energy flux

flat

cylinder

ball



Theory – dashed black curve

Photon energy, eV

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Thank you for attention!