New laser energy deposition algorithm for the radiation hydrodynamics code RALEF-2D

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Correct modeling of the laser beam evolution and power deposition on unstructured grids is a computationally and numerically challenging task. The two-dimensional hydrodynamics code RALEF-2D [1] with multigroup radiation transport and thermal conduction allows for simulations of laser-heated target configurations and matter at High Energy Density. A newly developped laser package includes laser-light refraction and reflections as well as power deposition in the overcritical plasma regime.

RALEF-2D

Mesh: two-dimensional, quadrilateral cells, multi-block, cartesian (x, y) or axisymmetric (r, z) coordinates

Hydrodynamics: local, based on the code CAVEAT [2], Arbitray-Lagrangian-Eulerian (ALE) remapping, Godunov-like Riemann solver, 2nd order in space

Thermal conduction: local, symmetrical-semi-implicit (SSI) method [3], 2nd order in space

Radiation transport: non-local, angular discretization with the S_n-method [4], SSI, short characteristics, 2nd order in space, discrete spectral groups $[\nu_j, \nu_{j+1}]$ with Planckian averaged absorption coefficient k_ν

Laser absorption: old model without refraction with same scheme as for radiation transport, deposition by inverse bremsstrahlung; new model with refraction see below

Supercomputing: parallelization with MPI / OpenMP

EOS and opacity models

THERMOS code (KIAM, Moscow): provides EOS, thermal conductivity and spectral opacities [5]; spectral opacities are generated from the Hartree-Fock-Slater equation for plasma ions with equilibrium level population (LTE)

FEOS package (Geothe University): provides EOS for any chemical element and arbitrary mixtures; Thomas-Fermi model and ionic model by Cowan; Maxwell construction for realistic EOS for simulations within liquid-vapor two-phase region [6]; library-based code design and visualization tool

Simulations of radiative properties

Example: heating of a carbon foam by hohlraum X-rays for energy loss measurements of heavy ions in partially ionized plasmas using the PHELIX laser and the Unilac at GSI [7]

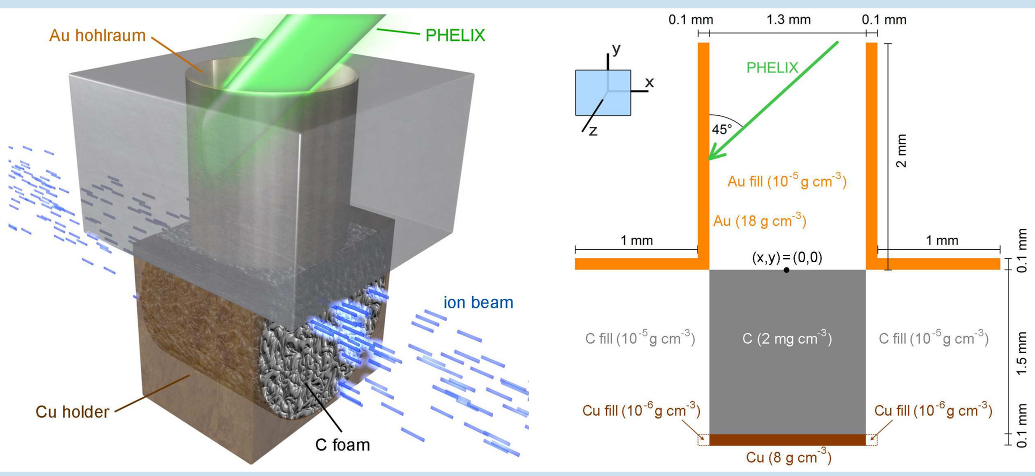

Figure 1: (left) Schematic view of the target geometry; (right) Simulation setup with dimensions and initial densities

PHELIX laser: $\lambda_l = 527$ nm, $E = 180$ J, $t_{pulse} = 1.4$ ns
Simulation on an ALE-mesh with ≈ 110000 cells

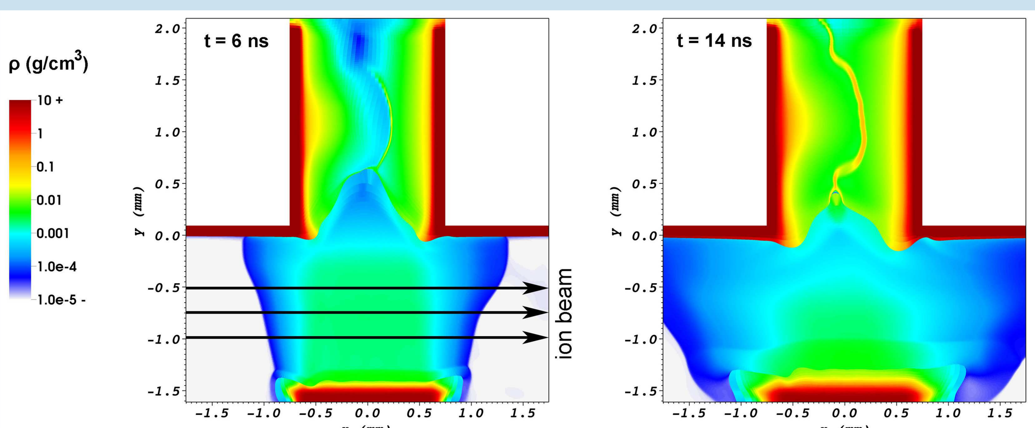

Figure 2: Color contour plot of the simulated matter density ρ of the whole experimental configuration at t $= 6$ and 14 ns

Laser reflections included in future simulations

Advanced laser simulation algorithm

Requirements: calculation of the refracted laser light distribution and of the deposited and reflected powers and the angular distribution of the reflected laser light close to and above the critical free electron density ($n_e \gtrsim n_c$)

Proposed solution: spatially discretize the incoming laser beam intensity, apply 2D geometrical optics raytracing approach with refraction for undercritical free electron densities ($n_e \ll n_c$), and augment it by a 1D wave optics solver for complex refractive indices σ ($n_e \gtrsim n_c$)

Computational scheme

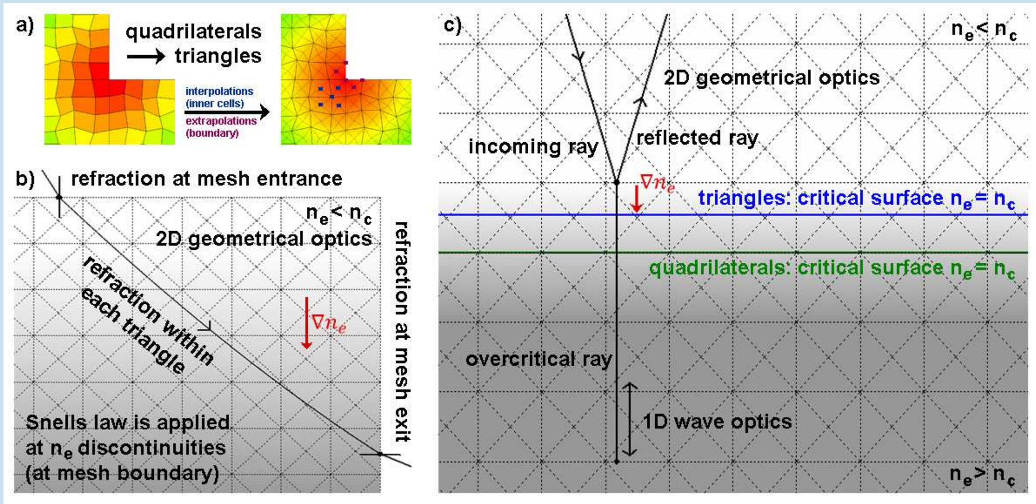

Figure 3: (a) Remapping of the quadrilateral mesh onto triangles; (b) Refraction by geometrical optics in the undercritical regime and by Snells law at the mesh entrance and exit; (c) Ray splittings according to the density gradient at the critical surface entry triangle

Quadrilateral grid is divided into triangles by means of bilinear interpolations and three-point boundary extrapolations

$\Rightarrow n_e(\vec{r})$ uniquely defined piecewise linear
Continuous transitions of the refracted rays are assured

Mesh boundary condition: refraction by Snells law

Split rays at critical surfaces into straight wave optics rays propagating parallel to the density gradient of the entry triangle ($n_e \gtrsim n_c$) and reflected geometrical optics rays

2D geometrical optics raytracing

On the basis of the eikonal equation [8] the equation of motion of a ray [9] for $n_e \ll n_c$ becomes:

$$d^2\vec{r}/dt^2 = -(c^2/2)(\vec{\nabla} n_e/n_c) \tag{1}$$

Deposited power on ray segment Δs in crossed triangle:

$$P_{dep} = P_0\left(1 - e^{-\kappa}\right), \quad \kappa = \Delta s \, \mathrm{Im}\,(\sigma) \tag{2}$$

P_0 – initial power, κ – optical depth, σ – complex refractive index of cell (per unit length, inverse bremsstrahlung)

1D wave optics solver

Crossed triangle segments define a piecewise-constant distribution of permittivities ϵ_j along the ray coordinate z

Solve Maxwells equations and calculate deposited, reflected, and transmitted ray energies from the field components $\vec{F}^s_j = (E_{x,j}, H_{y,j})$ for s- or $\vec{F}^p_j = (H_{x,j}, -E_{y,j})$ for p-polarization with the amplitudes $\vec{A}_j = \left(A^+_j, A^-_j\right)$ of the superposition of the incident and reflected waves

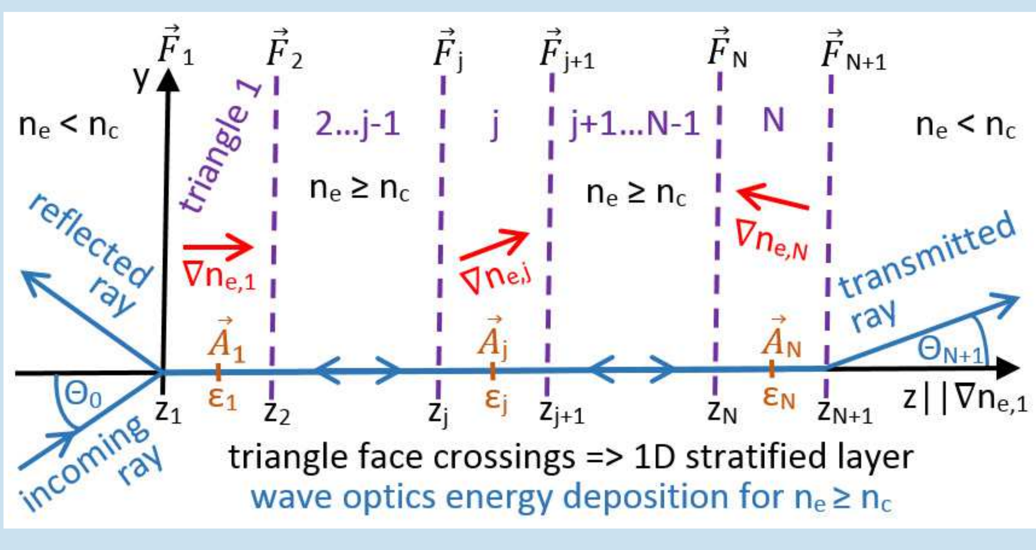

Figure 4: 1D wave optics solver for a stratified medium [8]

Quadratic density sphere test case

Quadratic density sphere [10] with radius R_{sp}:

$$n_e(r, z) = \left(1 - \sqrt{r^2 + z^2}/R^2_{sp}\right) n_c \leq n_c \tag{3}$$

Analytical trajectory solution for rays entering parallel to the z-coordinate ((r_a, z_a) – ray entry point):

$$r\,(t) = r_a \cosh\left(ct/R_{sp}\right) \tag{4}$$

$$z\,(t) = z_a \cosh\left(ct/R_{sp}\right) - R_{sp} \sinh\left(ct/R_{sp}\right) \tag{5}$$

$\Rightarrow$ Analytical exit point for all rays: $(r_e, z_e) = (R_{sp}, 0)$

L2 and maximum norms for truncation errors:

$$\delta Q^h_{L2} = \left[\left(\sum_{ik} \left(\vec{r}_{ik} - \vec{r}^{an}_{ik}\right)^2 \Delta t_{ik}\right) / \left(\sum_{ik} \Delta t_{ik}\right)\right]^{1/2} \tag{6}$$

$$\delta Q^h_m = \max_{ik} \left|\vec{r}_{ik} - \vec{r}^{an}_{ik}\right| \tag{7}$$

$h = \sqrt{l_r l_z/N}$ – cell size parameter, $l_{r,z}$ – mesh dimensions, N – number of triangles, $\vec{r}_{ik}$ – face intersection k of ray i, $\vec{r}^{an}_{ik}$ – analytical solution, Δt_{ik} traversal time for segment k

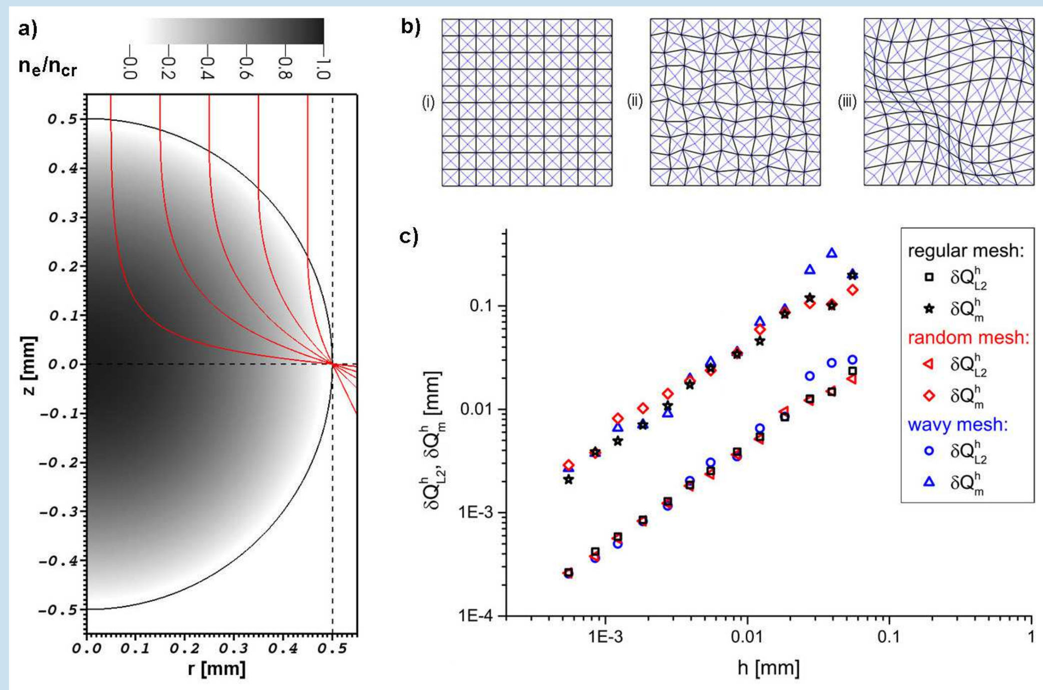

Figure 5: (a) Calculational domain with undercritical free electron density sphere of radius $R_{sp} = 0.5$ mm and five simulated rays; (b) Used grid types for the test: (i) orthogonal square grid, (ii) random grid, (iii) smooth wavy grid; (c) Size of truncation errors for 500 test rays determined by the Q^h_{L2} and Q^h_m norms (Eqns. 6 and 7)

Quadratic density trough test case

Quadratic density trough [9] with mesh heigth l_y:

$$n_e(y) = (2n_c/l^2_y)(y^2 - l_y y + l^2_y/2) \leq n_c \tag{8}$$

Analytical trajectory solution for rays entering perpendicular to free electron density gradient (y_a – ray entry point):

$$y\,(x) = \frac{l_y}{2} + \left(y_a - \frac{l_y}{2}\right) \cos\left(\sqrt{\frac{2}{1 - n_e\,(y_a)/n_c}}\frac{x}{l_y}\right) \tag{9}$$

Analytical optical depth solution for a quarter cosine-wavelength, fixed Coloumb logarithm $\ln\Lambda\,(y)$ and ionization $Z\,(y)$, and the temperature profile $T(y) \propto (n_e(y)/n_c)^{2/3}$:

$$\kappa = \mathrm{Im}\,(\sigma_0)\frac{2\pi}{l_y}\left(y^2_a + \frac{3l^2_y}{4} - l_y y_a\right), \quad \sigma_0 = \sigma(l_y/2) \tag{10}$$

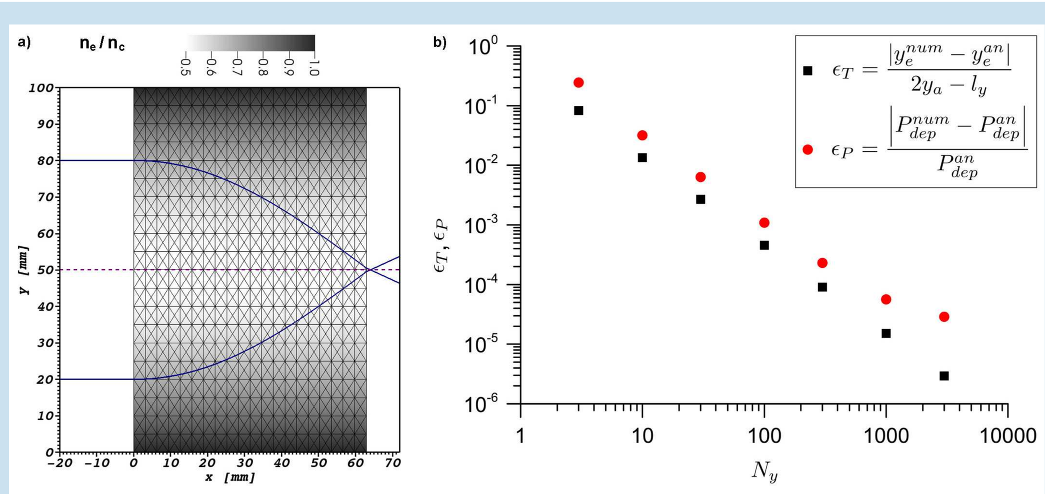

Figure 6: (a) Mesh setup and two simulated ray trajectories, mesh heigth $l_y = 100$ mm, trajectory entry points: $y_a = 20, 80$ mm, analytical trajectory exit point: $y^{an}_e = 50$ mm; (b) Dimensionless trajectory error ϵ_T at the mesh exit point and relative error ϵ_P in the summed-up deposited powers as functions of the number of quadrilateral cells in the y-direction N_y for a quarter cosine-wavelength

[1] M.M. Basko, An. Tauschwitz, J. Maruhn; GSI Report 2010-1 (GSI Scientific Report 2009), p. 410; [2] F.L. Addessio, J.R. Baumgardner, J.K. Dukowicz, N.L. Johnson, B.A. Kashiwa, R.M. Rauenzahn, C. Zemach; LANL, LA-10613-MS, Rev. 1 (1992); [3] E. Livne, A. Glasner; J. Comp. Physics **58** (1985) 59; [4] B.G. Carlson; in Methods in Computational Physics, p. 1, Academic Press, New York and London (1963); [5] A.F. Nikiforov, V.G. Novikov, V.B. Uvarov; "Quantum-Statistical Models of Hot Dense Matter"; Birkhäuser (2005); [6] S. Faik, M.M. Basko, An. Tauschwitz, I. Iosilevskiy, J.A. Maruhn; High Energy Density Physics 8 (2012) 349; [7] S. Faik, An. Tauschwitz, M.M. Basko, J.A. Maruhn, O. Rosmej, T. Rienecker, V.G. Novikov, A.S. Grushin; High Energy Density Physics 10 (2014) 1574; [8] M. Born, E. Wolf; "Principles of Optics"; Cambridge University Press (2005); [9] T.B. Kaiser; Physical Review E 61 (2000) 895; [10] I.P. Tsygvintsev, A.Y. Krukovskiy, V.G. Novikov, I.V. Popov; KIAM Preprint 41 (2012).