Radiation-hydrodynamics simulations of matter at high energy density driven by laser and ion beams

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Outline

- Radiation hydrodynamics code RALEF-2D
- Laser driven hot dense plasmas
    - Homogeneous fully ionized plasma layer
    - Plasma at extremely high temperatures
    - Plasma heating by hohlraum radiation
- Warm Dense Matter Regime

Radiation hydrodynamics code RALEF-2D

Equations of hydrodynamics

The newly developed **RALEF-2D** code is based on a one-fluid, one-temperature hydrodynamics model in two spatial dimensions (either x,y, or r,z):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0,$$

$$\frac{\partial \left(\rho \vec{u} \right)}{\partial t} + \nabla \cdot \left(\rho \vec{u} \otimes \vec{u} \right) + \nabla p = 0,$$

$$\frac{\partial \left(\rho E \right)}{\partial t} + \nabla \cdot \left[\left(\rho E + p \right) \vec{u} \right] = \nabla \cdot \left(\kappa \nabla T \right) + Q_r + Q_{dep},$$

$$E = e + \frac{u^2}{2}, \quad p = p(\rho, e)$$

$\nabla \cdot \left(\kappa \nabla T \right)$ – energy deposition by thermal conduction (local), Q_r – energy deposition by radiation (non-local), Q_{dep} – eventual external heat sources.

Radiation transport

Transfer equation for radiation intensity I_ν in the quasi-static approximation:

$$\cancel{\frac{1}{c}\frac{\partial I_\nu}{\partial t}} + \vec{\Omega}\cdot\nabla I_\nu = k_\nu\left(B_\nu - I_\nu\right), \quad I_\nu = I_\nu\left(t,\vec{x},\nu,\vec{\Omega}\right), \quad B_\nu = B_\nu\left(\nu,T\right)$$

Quasi-static approximation: radiation transports energy infinitely fast (compared to the fluid motion) $\Rightarrow$ the energy residing in radiation field at any given time is infinitely small !

In the present version, the absorption coefficient k_ν and the source function $B_\nu = B_\nu(T)$ are calculated in the LTE approximation.

Coupling to the fluid energy equation:

$$Q_r = -\nabla\cdot\left(\int d\nu \int \vec{\Omega} I_\nu \, d\vec{\Omega}\right) = \int_{4\pi} d\vec{\Omega} \int k_\nu \left(I_\nu - B_\nu\right) d\nu$$

Radiation transport adds 3 extra dimensions (two angles and the photon frequency) $\Rightarrow$ **the 2D hydrodynamics becomes a 5D radiation hydrodynamics !**

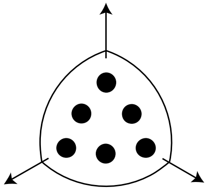
The RALEF-2D code

The newly developed two-dimensional radiation-hydrodynamics code RALEF-2D is based on:

- hydrodynamics is built upon the CAVEAT-2D (LANL, 1990): multi-block structured quadrilateral mesh, 2nd-order Godunov scheme, conservative, mesh adaptation by applying the ALE (arbitrary Lagrangian-Eulerian) technique

SSI (symmetric semi-implicit) method of E.Livne & A.Glasner (1985), used to incorporate **thermal conduction** and **radiation transport** into the 2D Godunov method

- thermal conduction: 2nd order in space, conservative (M.Basko, J.Maruhn & An.Tauschwitz, J.Com.Phys., **228**, 2175, 2009);
- radiation transport: S_n method along short characteristics (n(n+2) photon propagation directions over 4π), 1st order in space, non-conservative, recovers the diffusion limit (optically thick cells)

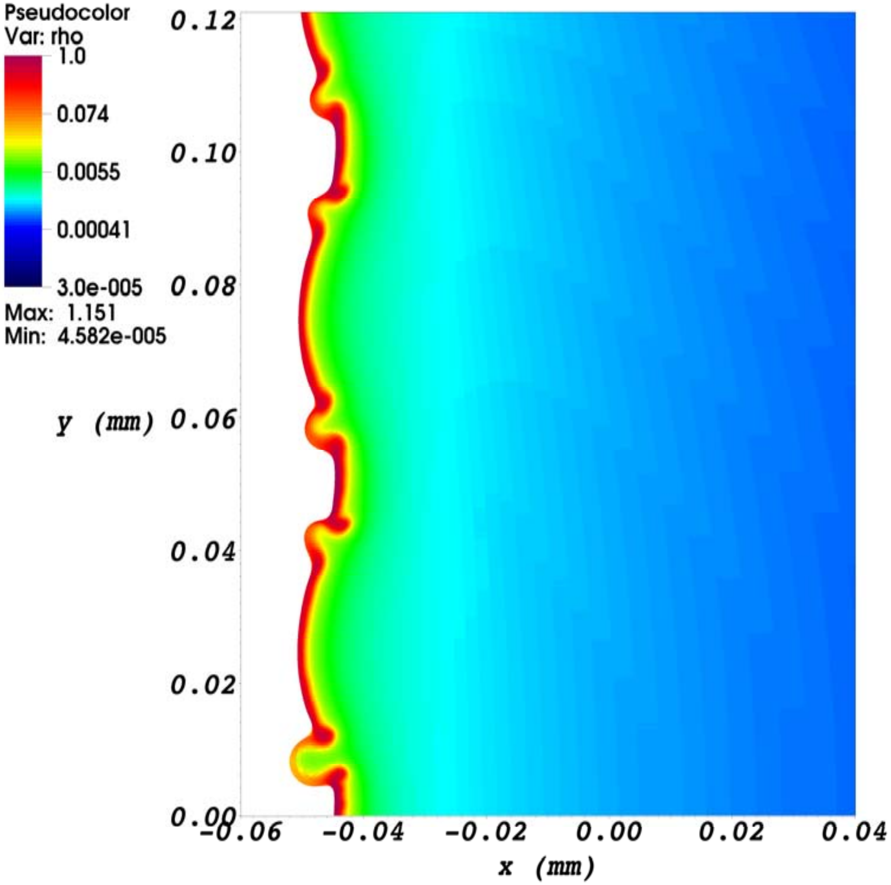


S_6

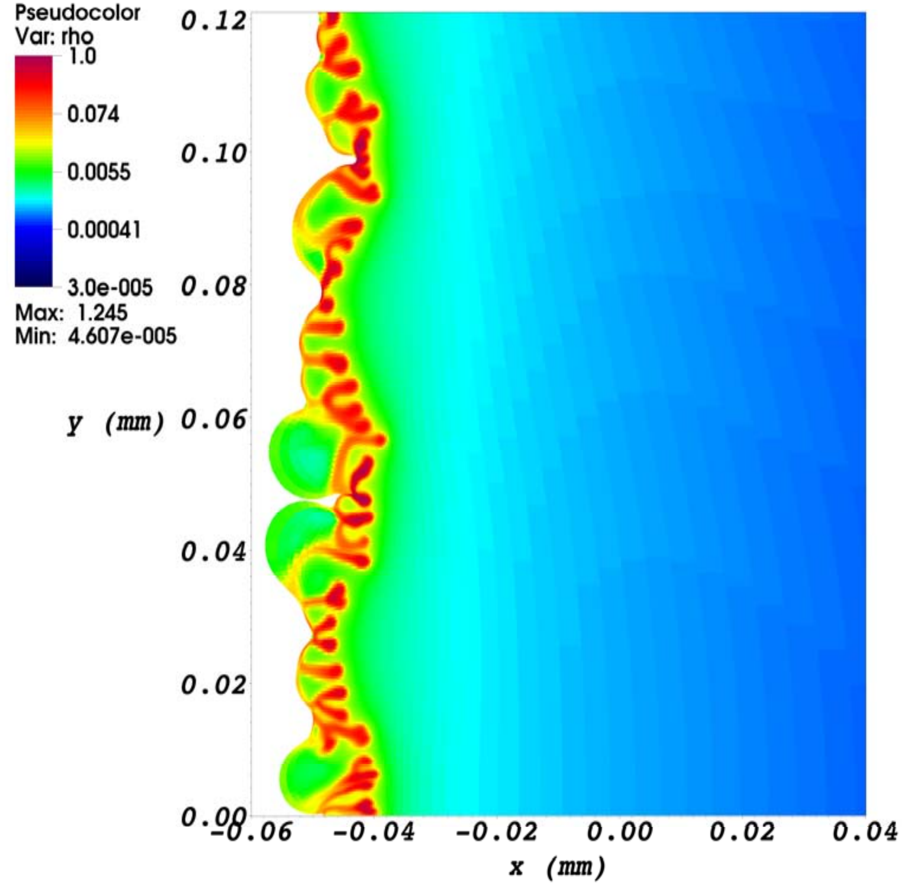
Importance of the 2-nd order + ALE

Non-linear stage of the Rayleigh-Taylor instability of a laser-irradiated thin carbon foil

RALEF: 1-st order



RALEF: 2-nd order



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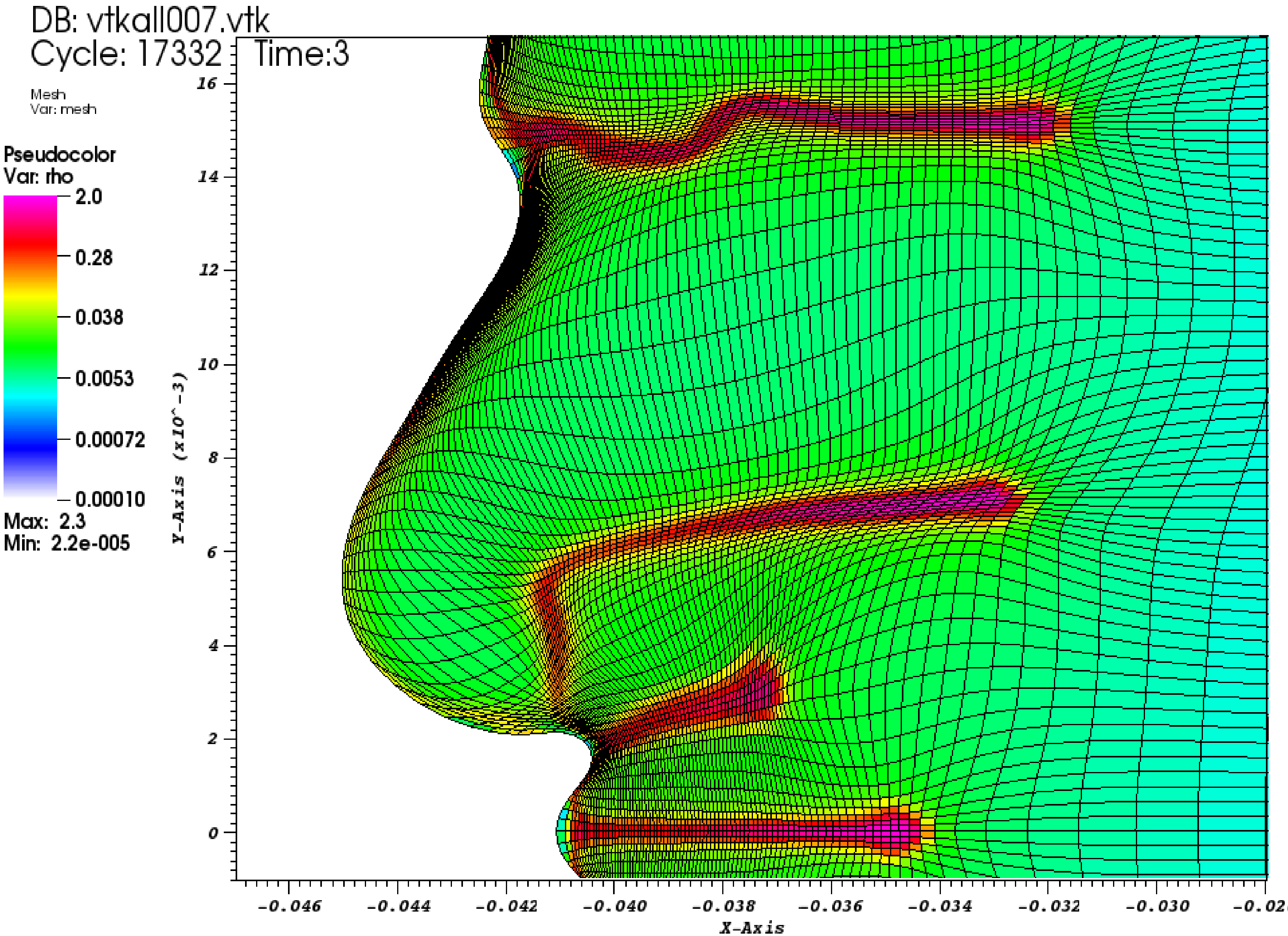


GSI

EOS options in RALEF-2D

The EOS model must provide

$$p = p(\rho,e), \quad c^2 = c^2(\rho,e), \quad T = T(\rho,e), \quad c_V = c_V(\rho,e), \quad z = z(\rho,e), \quad a_{Du} = a_{Du}(\rho,e).$$

Analytical EOS models:

1. polytropic gas: $p = (\gamma - 1)\rho e, \quad e = c_V T, \quad a_{Du} = \frac{1}{2}(\gamma + 1), \quad c_V, z = const$
2. linear EOS: $p = (\rho - \rho_0)\left[c_1\rho_0 + c_2\left|\rho - \rho_0\right|\right] + \left(c_3\rho_0 + c_4\rho\right)e, \quad T = (e - e_{cold})/c_V, \ \ldots$

. . . .

Tabular EOS models:

7. general logarithmic-table (GLT) EOS with different source EOS models:

   Basko (Z = 1—13, 18, 22,26,28,29,36,40,42, 47, 54,55,74,79,82,83,92)

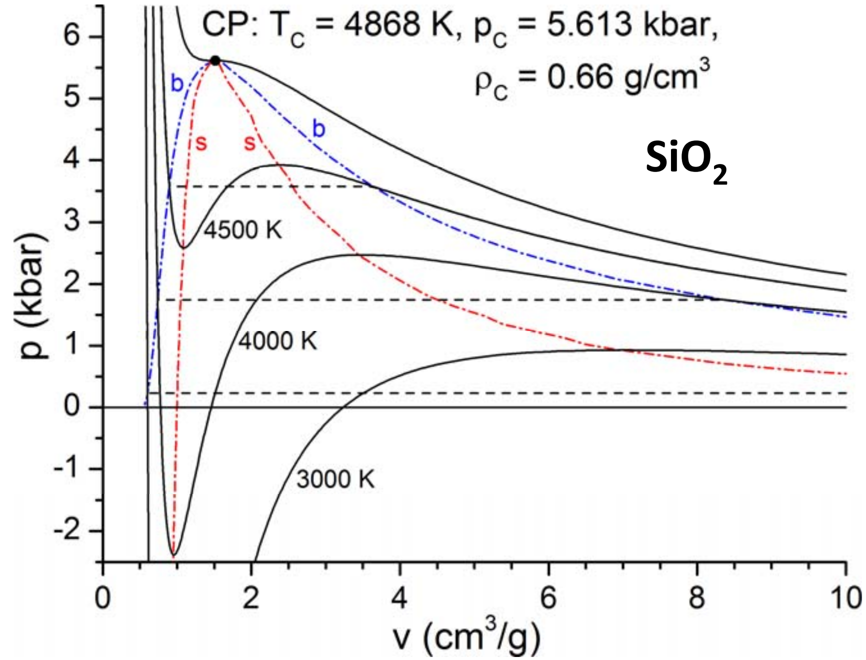
   Novikov (THERMOS code (KIAM, Moscow); Z=1,6,13,22,29,74,79)

   FEOS (any Z, mixtures)

8. SESAME tabular EOS

The FEOS (Frankfurt EOS) package*

- provides single or two-temperature EOS data (p, ε, s, zion) as function of (ρ, T)
- EOS generation for arbitrary mixtures
- non-equilibrium EOS or Maxwell-construction



Electronic EOS: Thomas-Fermi statistical model corrected for chemical bonding

Ionic EOS: Interpolations between the Debye solid, normal solid and liquid states

Package structure:

- FEOS library (C/Fortran interface)
- FEOS table generation tool
- SHOWEOS table visualization tool

Input:

T_{ref}, ρ_{ref}, and bulk modulus K_{ref} at p=0
Critical point T_c, p_c, ρ_c (if known)

* http://th.physik.uni-frankfurt.de/~faik/feos.php
based on the QEOS model (1988), R. M. More et al., Phys. of Fluids 31
and the code MPQeos (1999), A. Kemp et al., MPQ Report 229

Opacity options in RALEF-2D

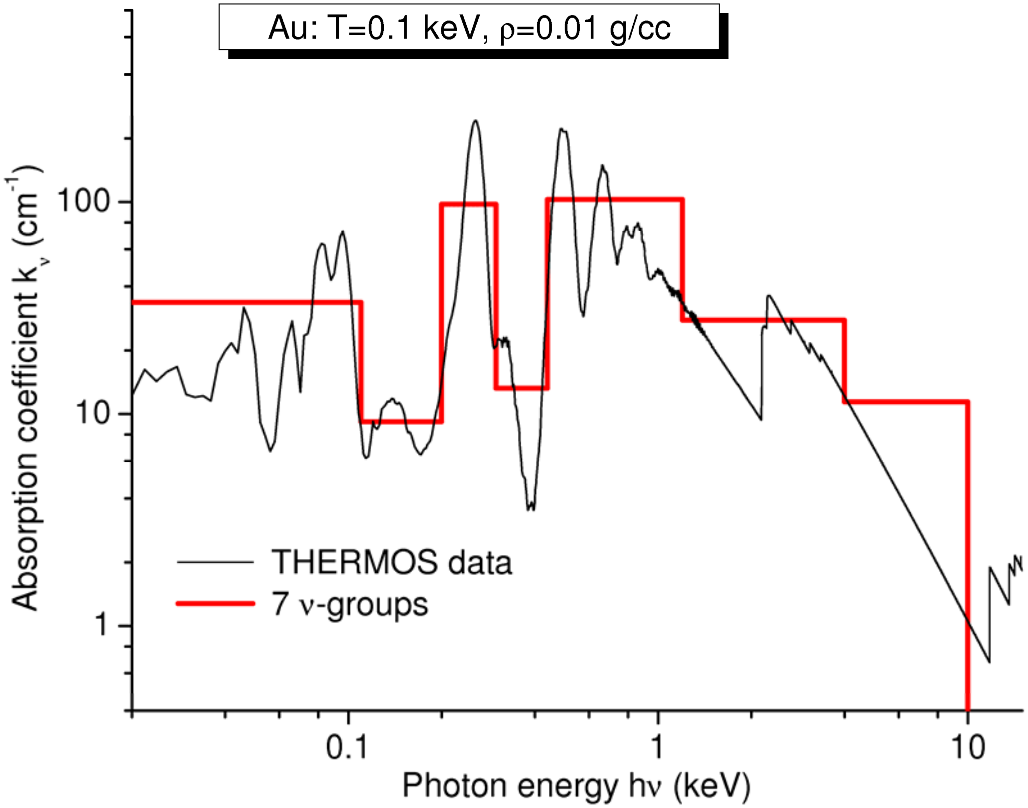
Here we profit from many years of a highly qualified work at KIAM (Moscow) in the group of Nikiforov-Uvarov-Novikov (the THERMOS code based on the Hartree-Fock-Slater atomic modeling).

Opacity options:

1. power law,
2. ad hoc analytical,
3. inverse bremsstrahlung (analytical),

. . . .

7. GLT tables (source opacities from Novikov)

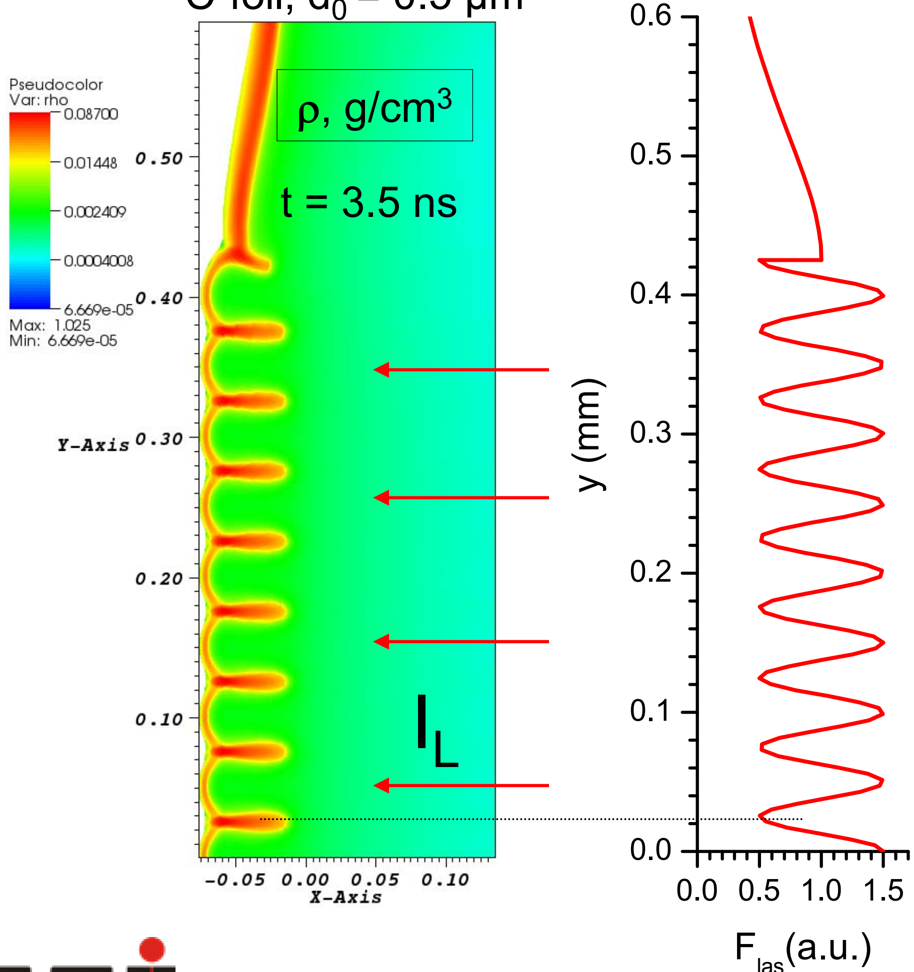


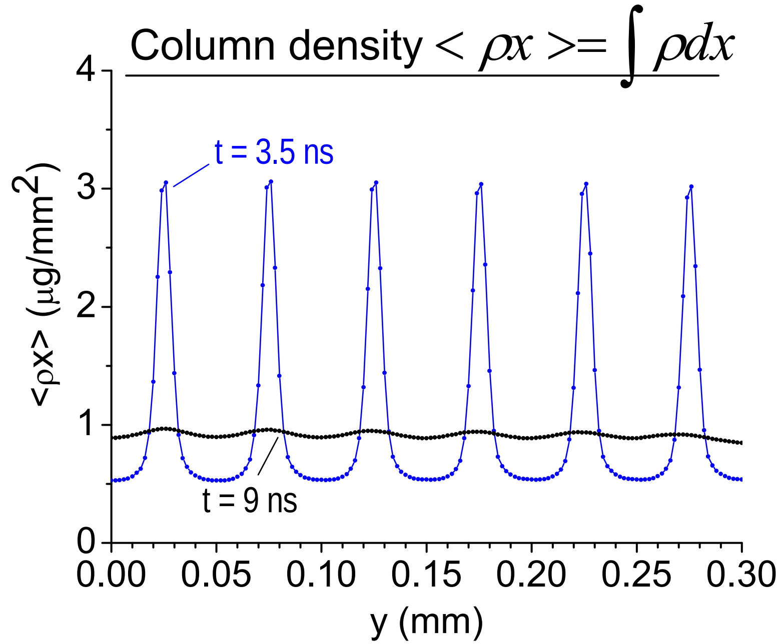
Laser driven hot dense plasmas

Homogeneous fully ionized plasma layer

Application at GSI: direct-driven plasma target for ion-stopping measurements

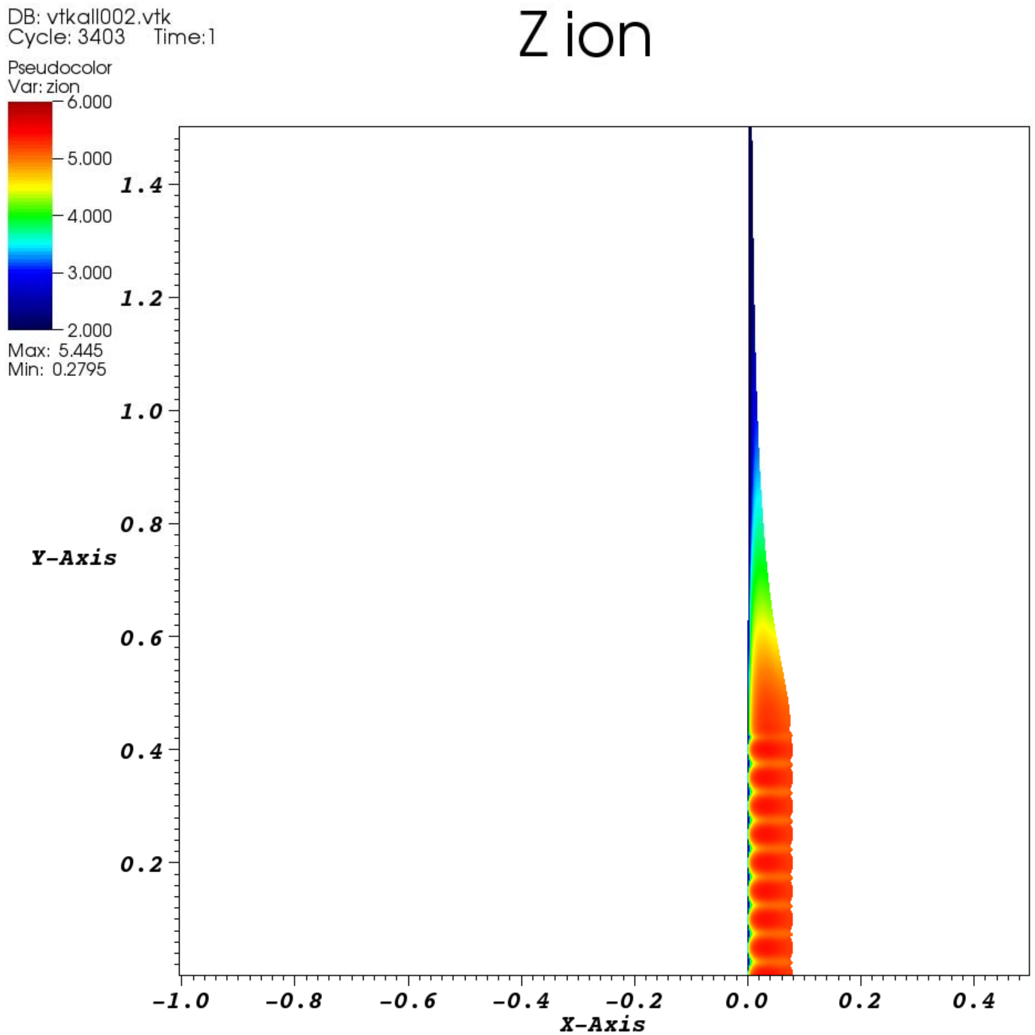
Phelix laser (2ω): $I_L = 5\cdot10^{11}$ W/cm^2, $\tau_b = 11$ ns, focus 1 mm, strongly modulated laser spot!



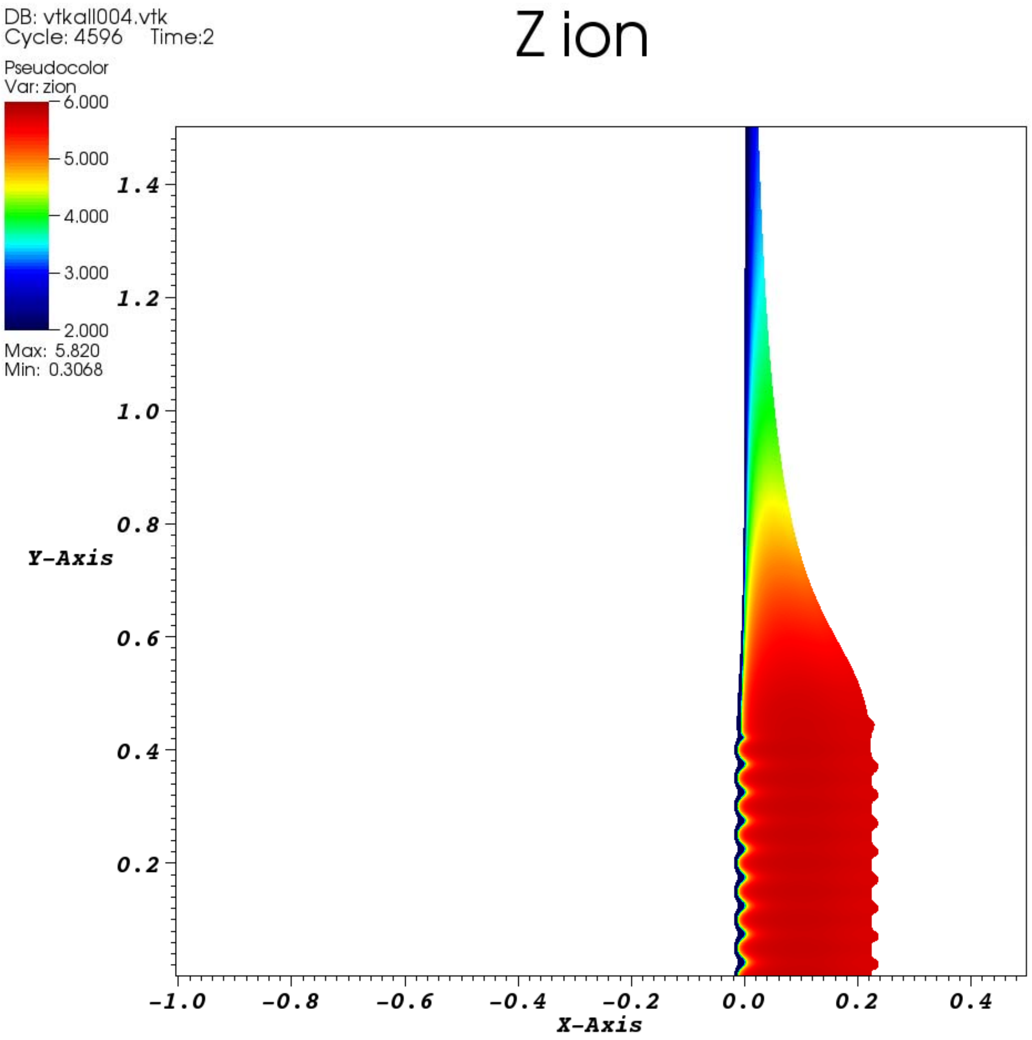


- The foil breaks into clumps
- By t = 9 ns the clumps dissipate mainly due to thermal radiation
- Problem: no full ionization for the 1-sided heating!

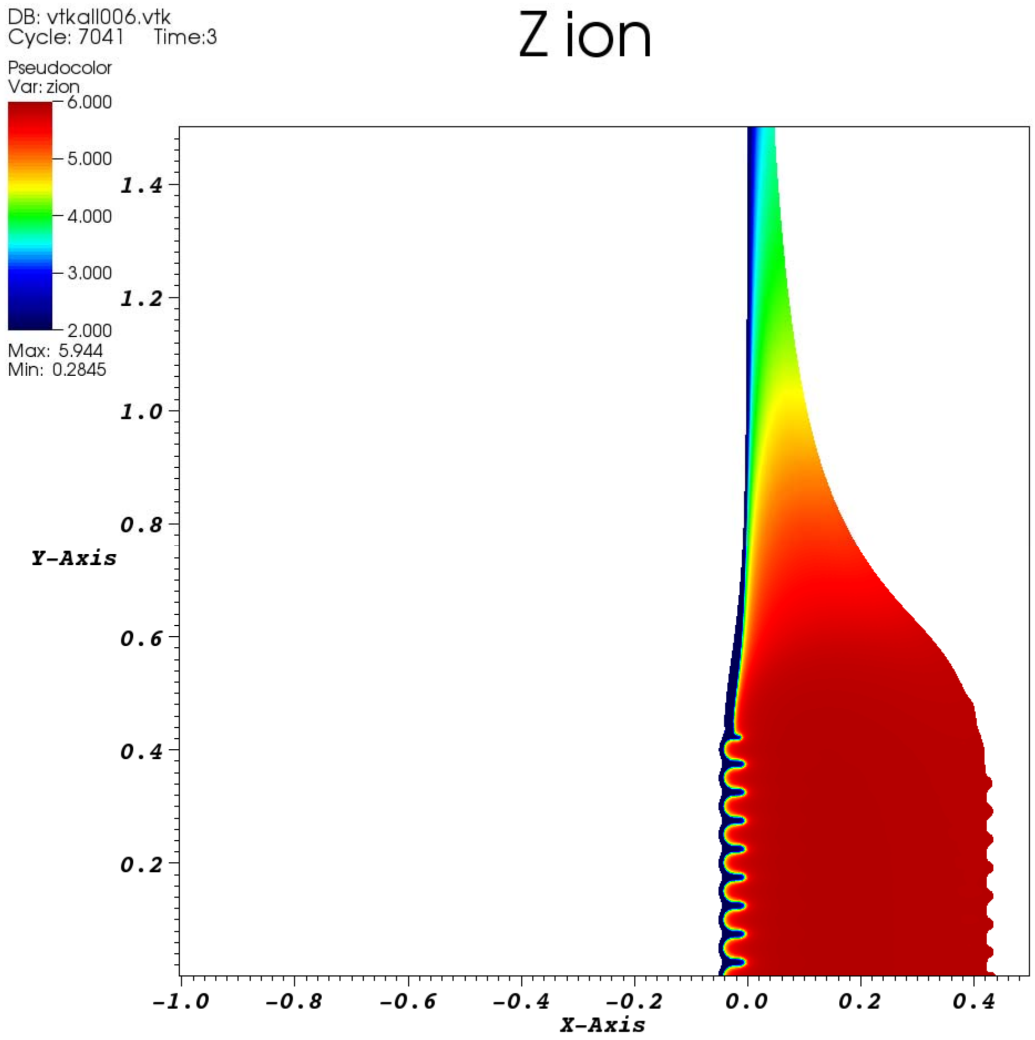
Homogeneous fully ionized plasma layer (2)



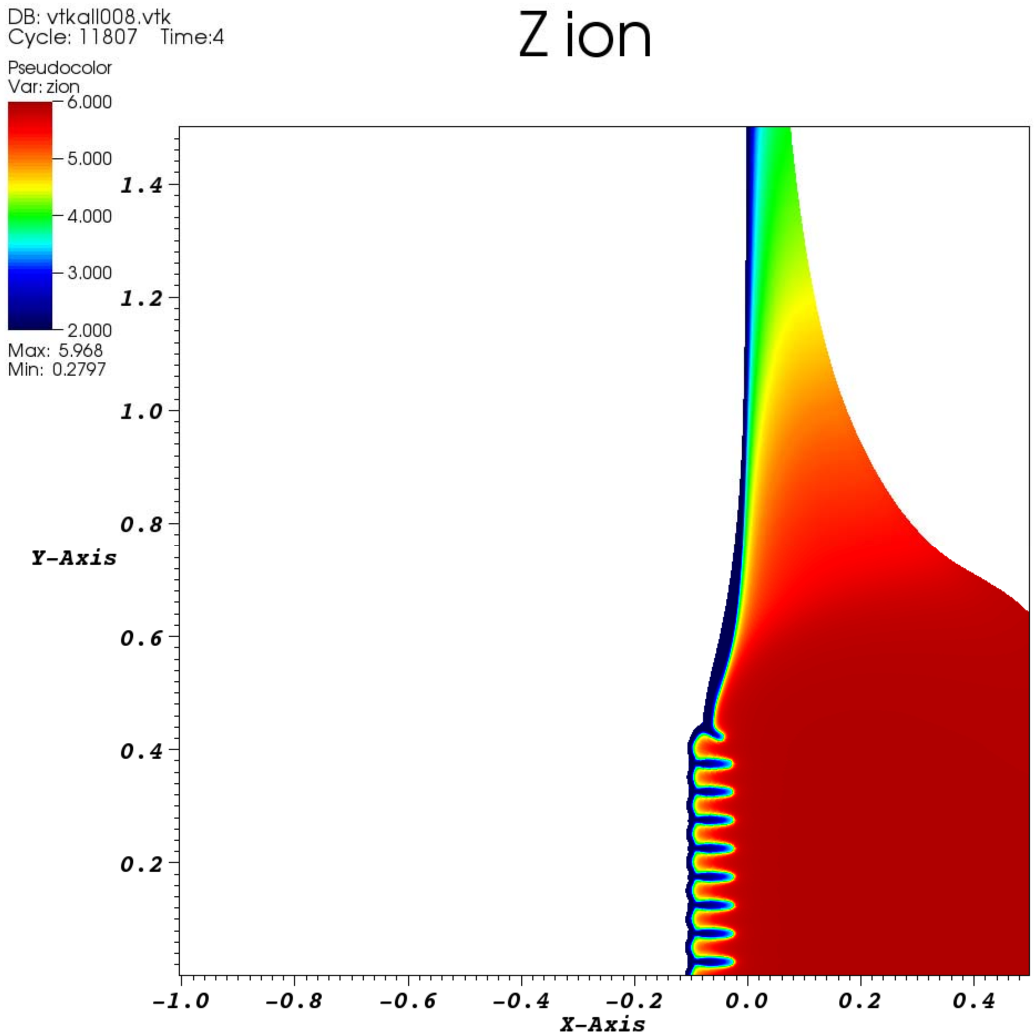
Homogeneous fully ionized plasma layer (2)



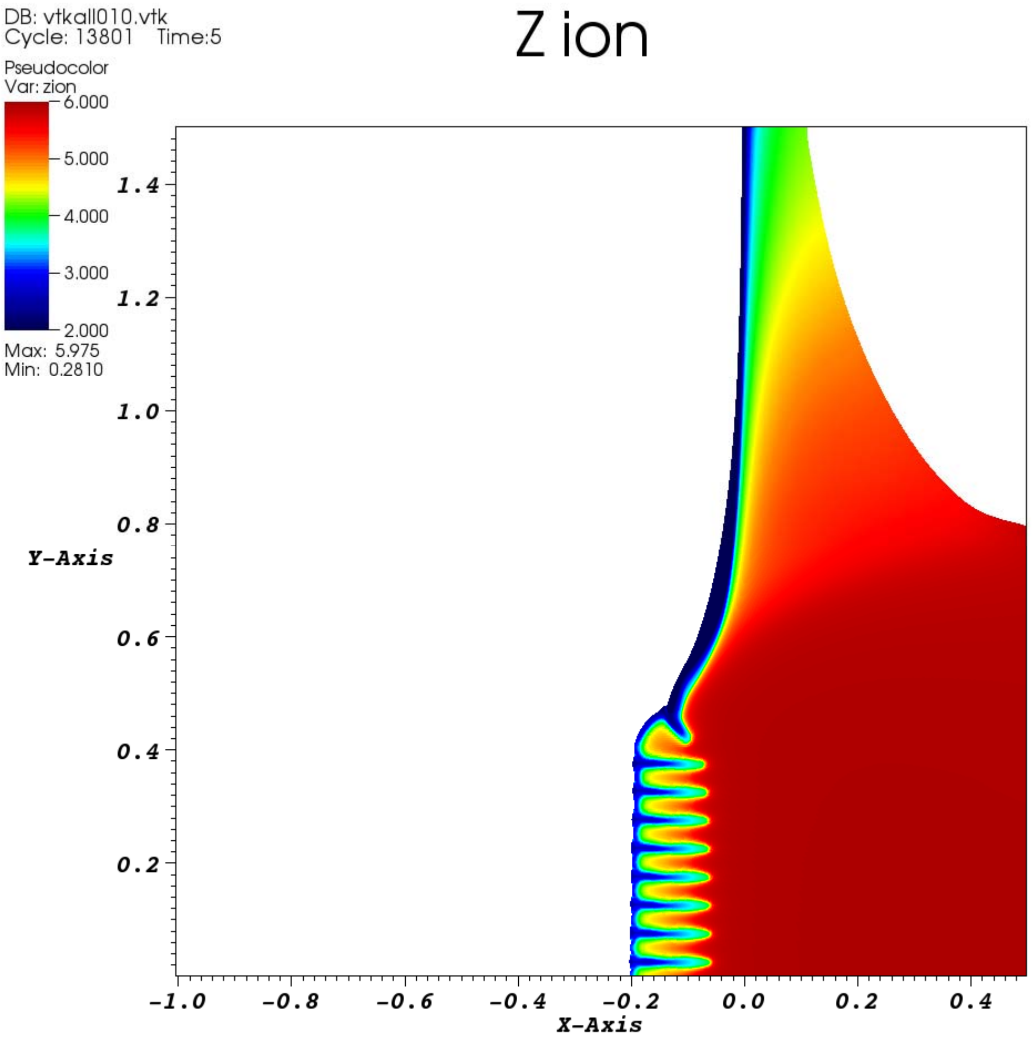
Homogeneous fully ionized plasma layer (2)



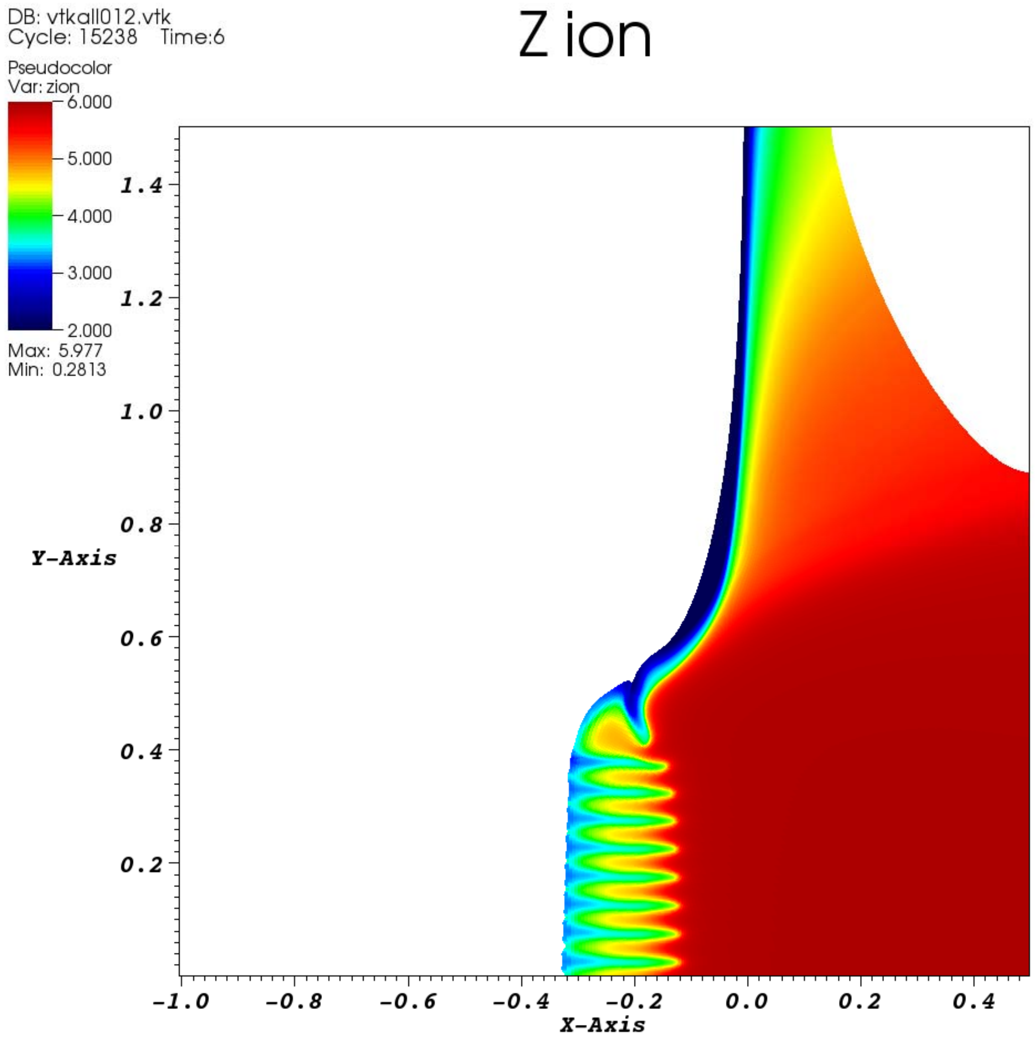
Homogeneous fully ionized plasma layer (2)



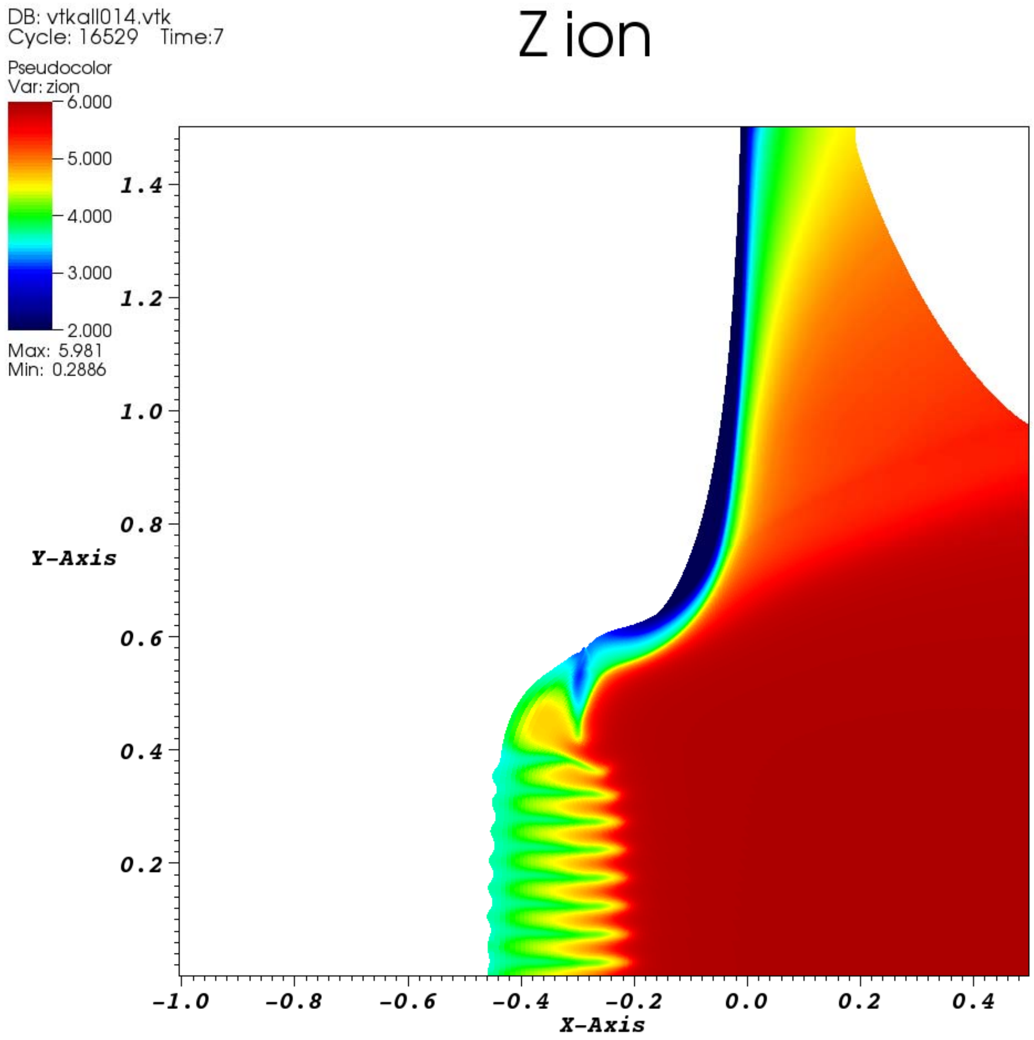
Homogeneous fully ionized plasma layer (2)



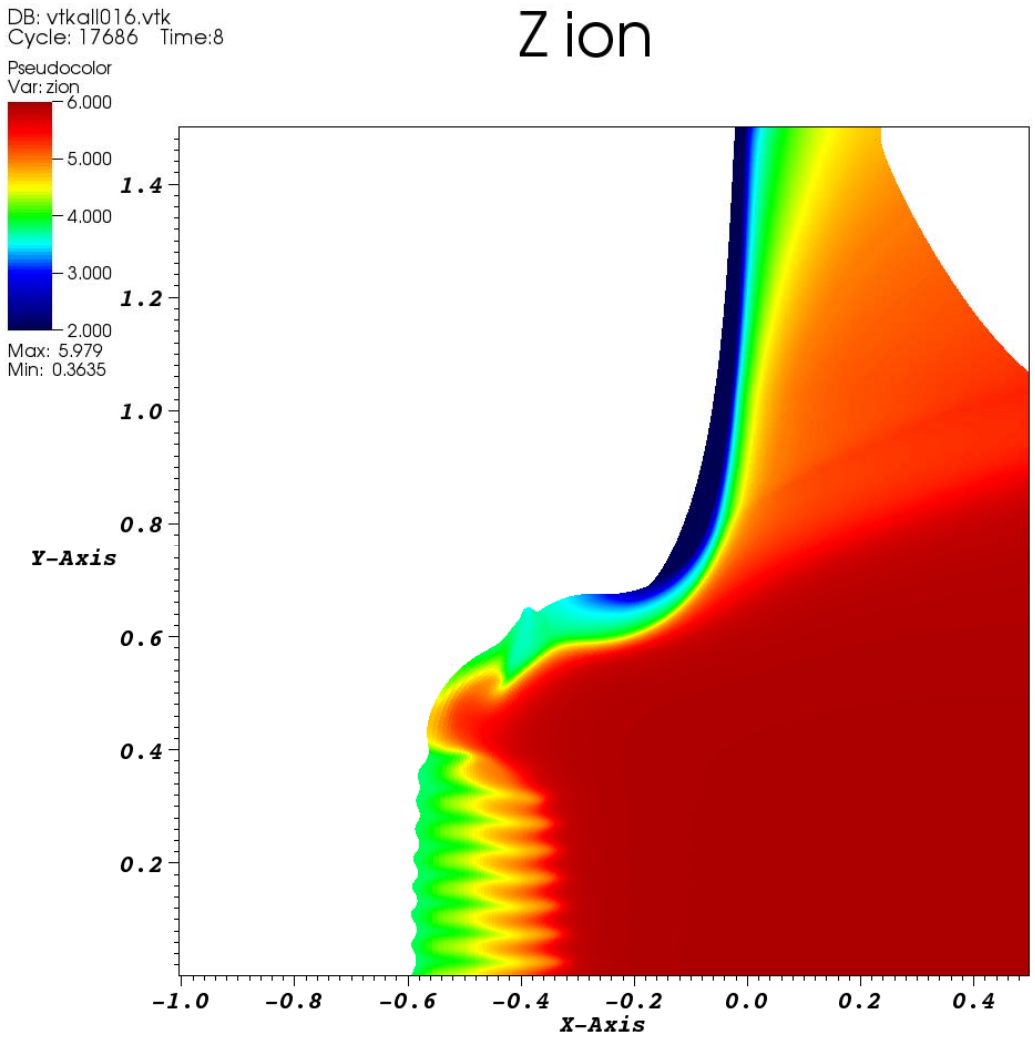
Homogeneous fully ionized plasma layer (2)



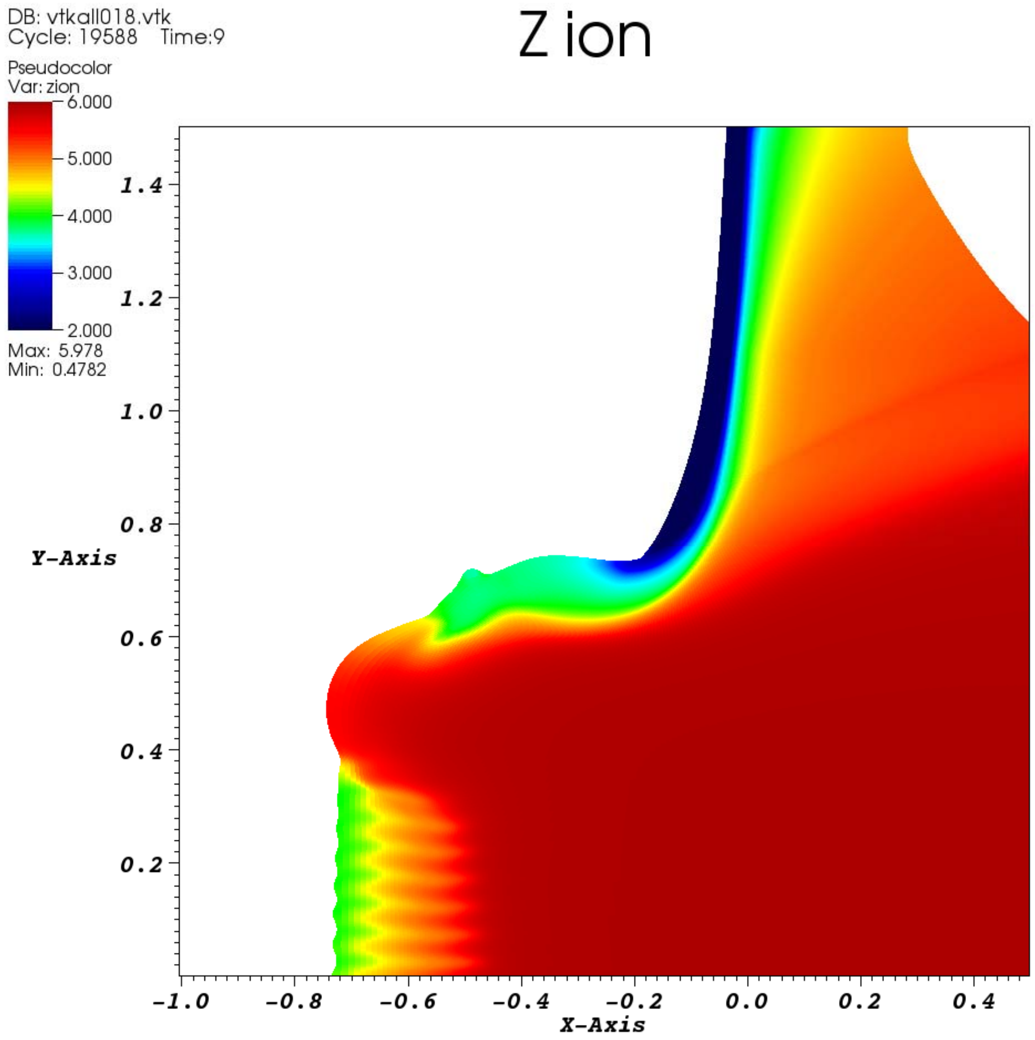
Homogeneous fully ionized plasma layer (2)



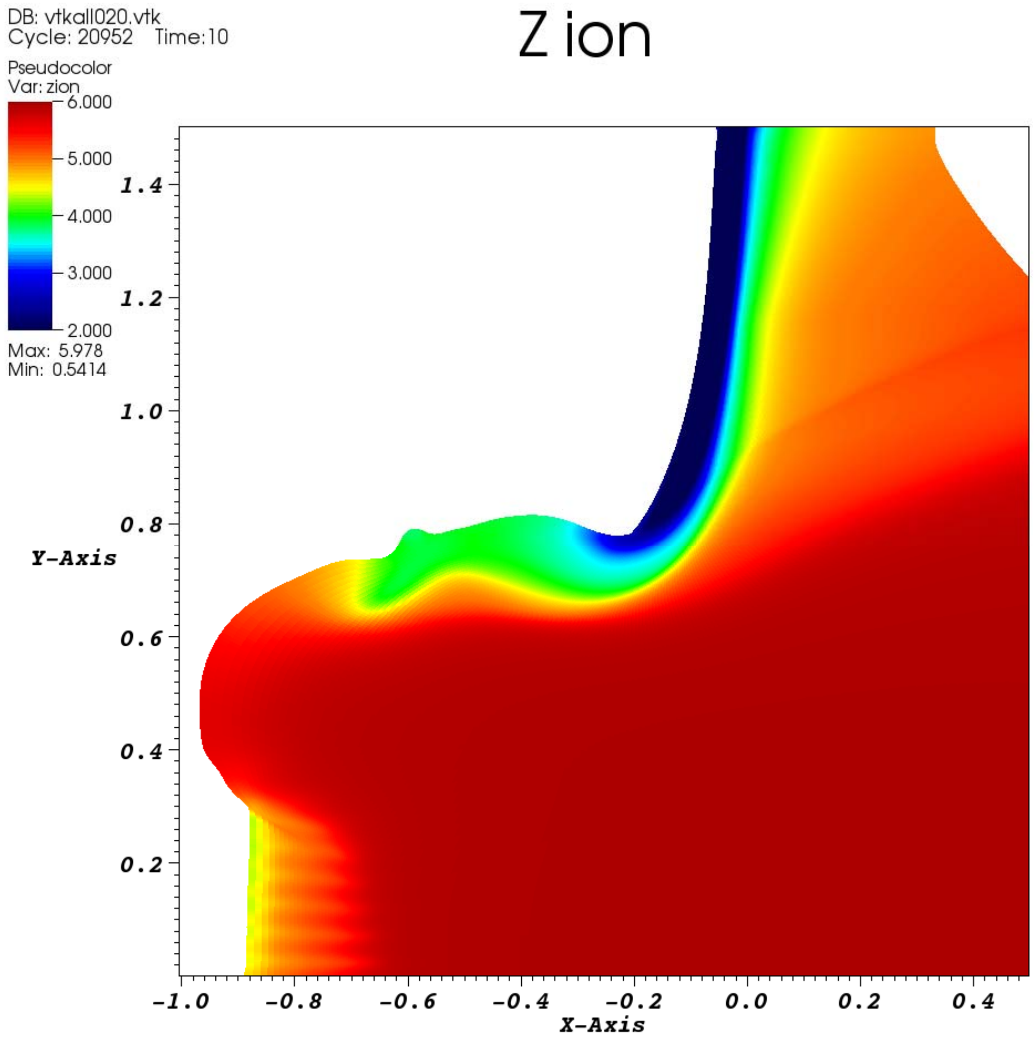
Homogeneous fully ionized plasma layer (2)



Homogeneous fully ionized plasma layer (2)



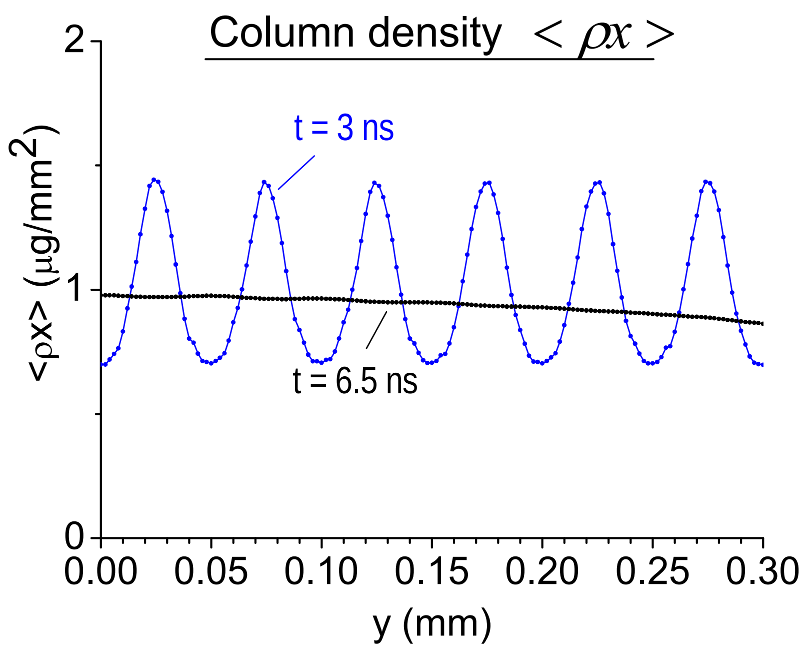
Homogeneous fully ionized plasma layer (2)

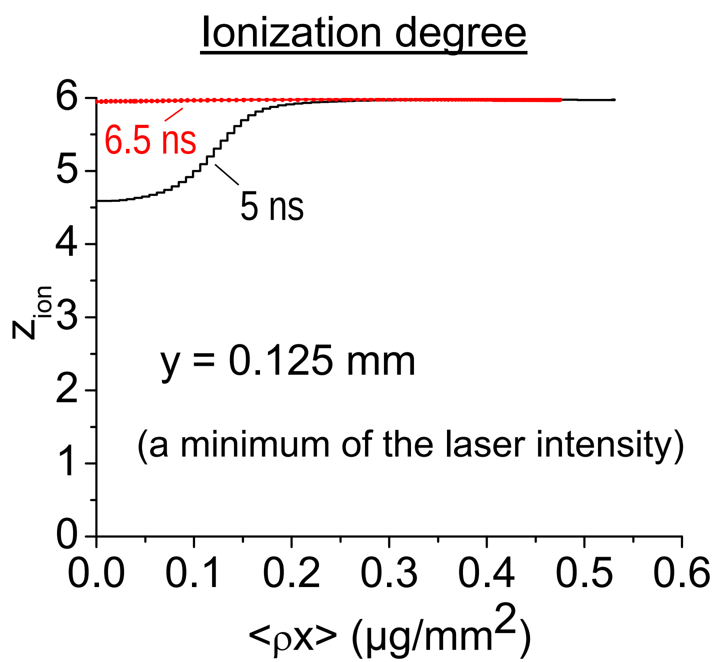


Homogeneous fully ionized plasma layer (3)

Solution: irradiation of a foil from both sides by two laser beams.

At GSI: Phelix + nhelix lasers; almost identical beam parameters.





- By t = 6.5 ns the modulation of $< \rho x >$ drops and the plasma column becomes fully ionized to $Z_{ion} = 6$
- A strongly non-uniform direct laser beam produces a uniform plasma column

Plasma at extremely high temperatures

Nuclear **E**xcitation by **E**lectronic **T**ransition (NEET) experiment (PHELIX proposal P059)
Spokesperson: F. Hannachi, CENBG, France

Goal: study nuclear excitation and de-excitation rates depending on plasma conditions

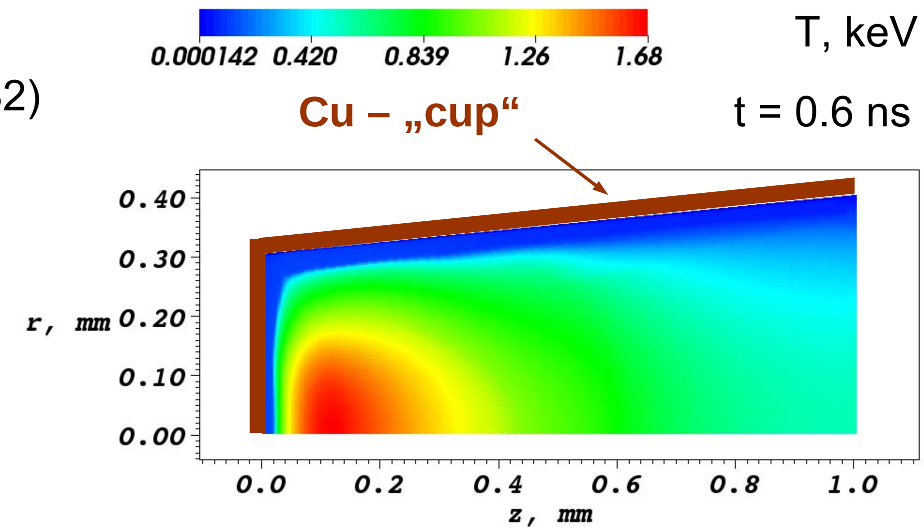
Experiment:
- UNILAC ions to create isomers
- PHELIX laser to heat the target and to excite the isomers using NEET

⇒ temperatures of a few keV must be achieved

At the experiment: Ge primary target (Z=32)
(EOS and opacities not yet available)
⇒ First simulations made with Cu (Z=29)

Optimum PHELIX parameters (2ω):

Energy E_l = 150 J
Pulse τ_b = 1ns
Focal spot r_b = 150 μm

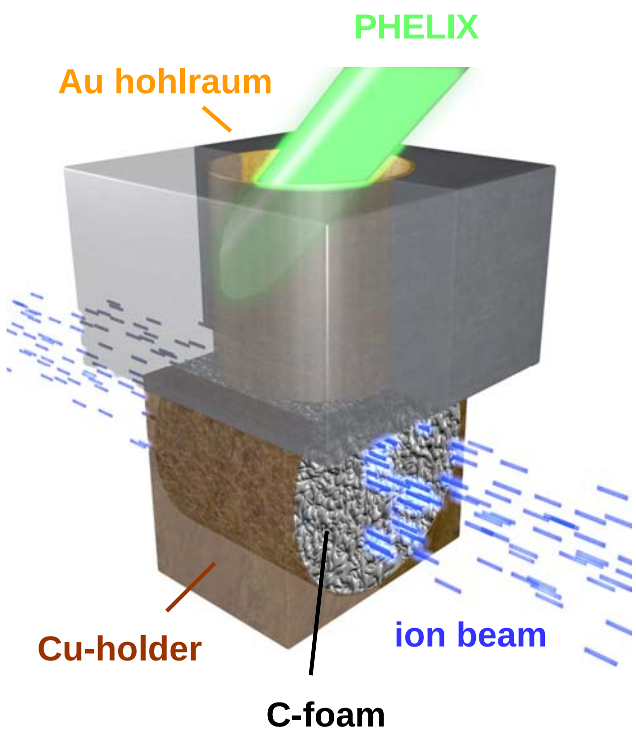


- 10^{18} highly ionized ($Z_{ion} \geq 26$) ions at a plasma temperature above1 keV will be generated
- the „cup“ helps to increase the number of ions by a factor 1.5-2 over a planar target

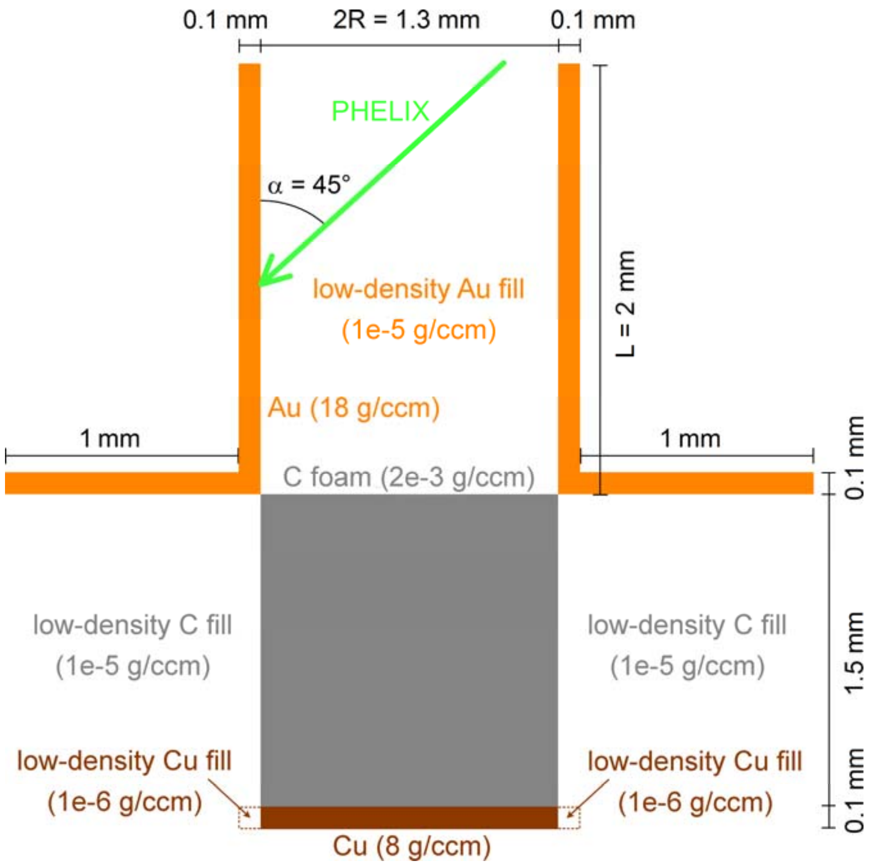
Plasma heating by hohlraum radiation

Application at GSI: ion-stopping measurements in plasma

Experimental setup



Simulation setup



PHELIX laser (2ω)

Deposited energy: E_l = 180 J, τ_b = 1.2 ns

Gaussian spot, FWHM = 200 μm

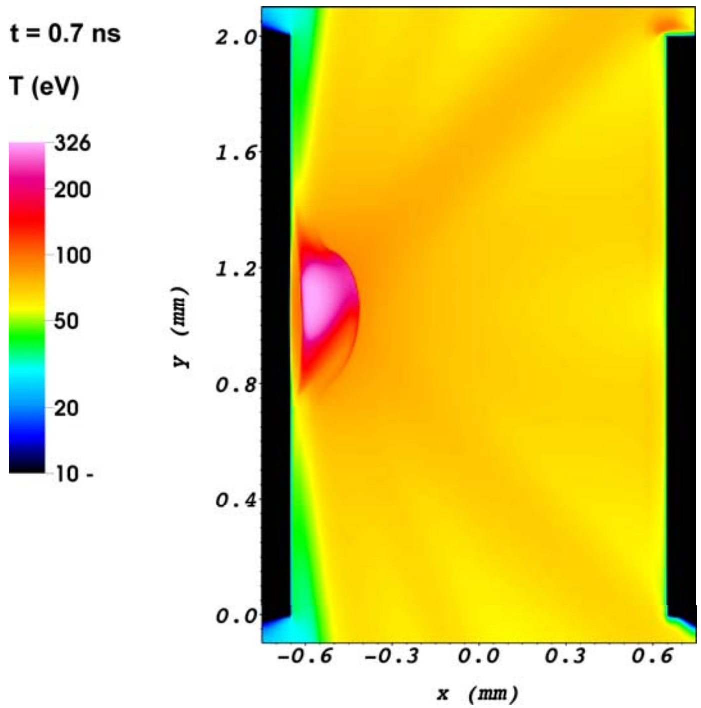
Infinite extension along z-direction is assumed

In the 2D configuration: E^{2D}_l = 122.8 J/mm

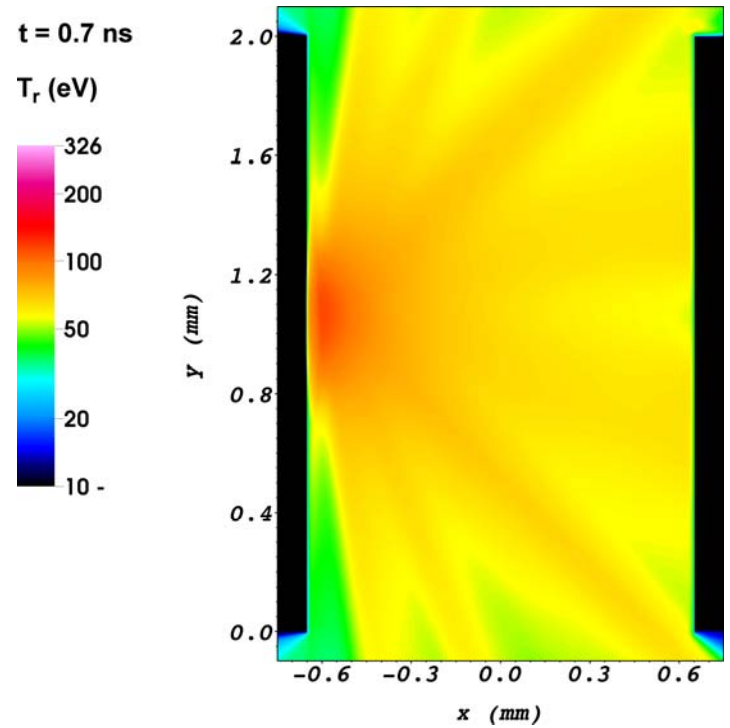
Plasma heating by hohlraum radiation (2)

Plasma temperature, T and radiation temperature, T_r in the hohlraum during the laser pulse.

T , eV



T_r , eV

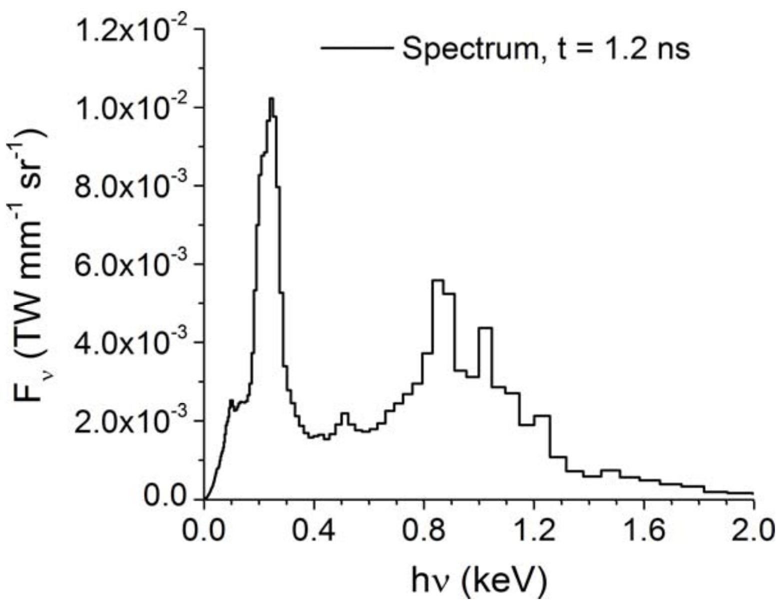


„Ray-effect“ due to discretization of the angular dependence of $I_\nu(\vec{x},\vec{\Omega})$ in the radiation transport algorithm (drawback of the S_n method).

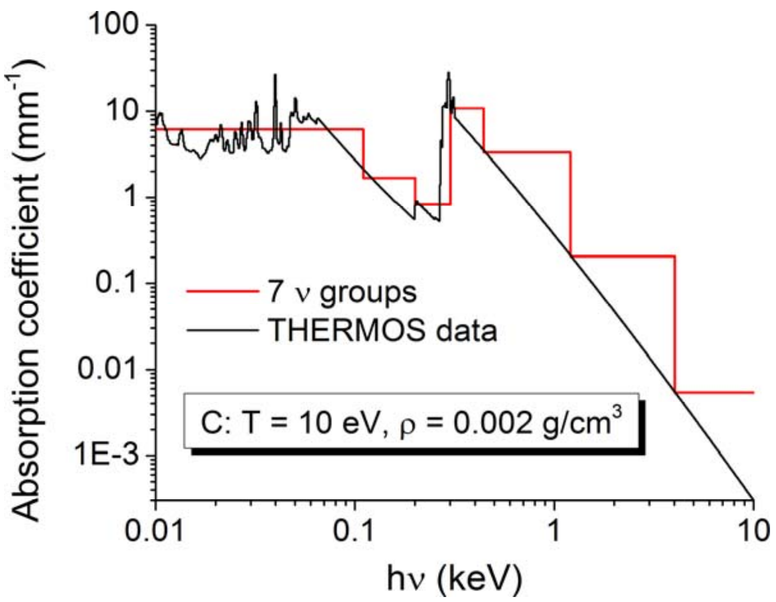
Plasma heating by hohlraum radiation (3)

Radiation emitted by the hohlraum is utilized to heat a low-Z foam

Hohlraum spectrum



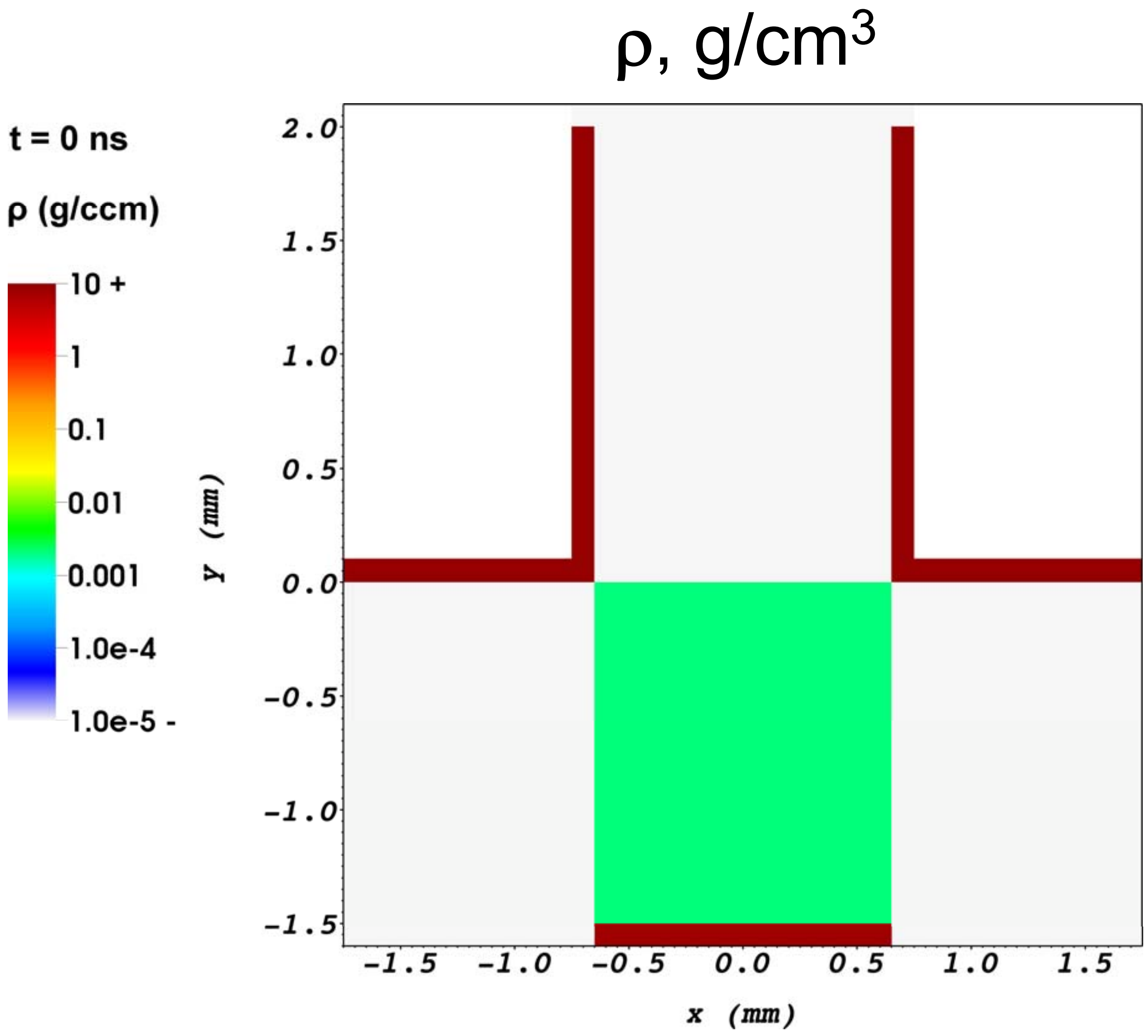
Opacities of carbon



Hot laser spot ⇒ strongly non-Planckian spectrum

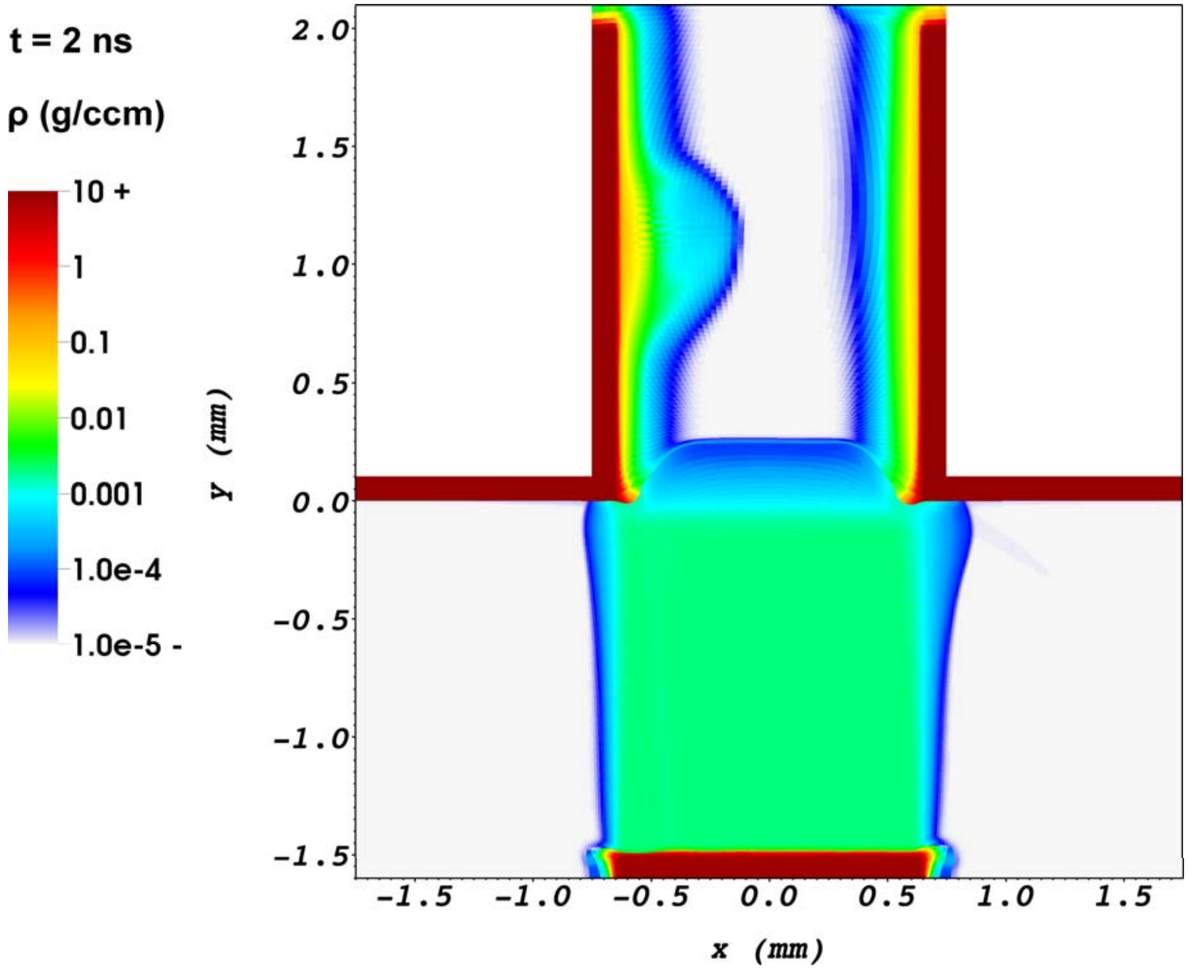
The energies of the X-rays emitted out of the hohlraum go well together with the absorption coefficient of carbon.

Plasma heating by hohlraum radiation (4)



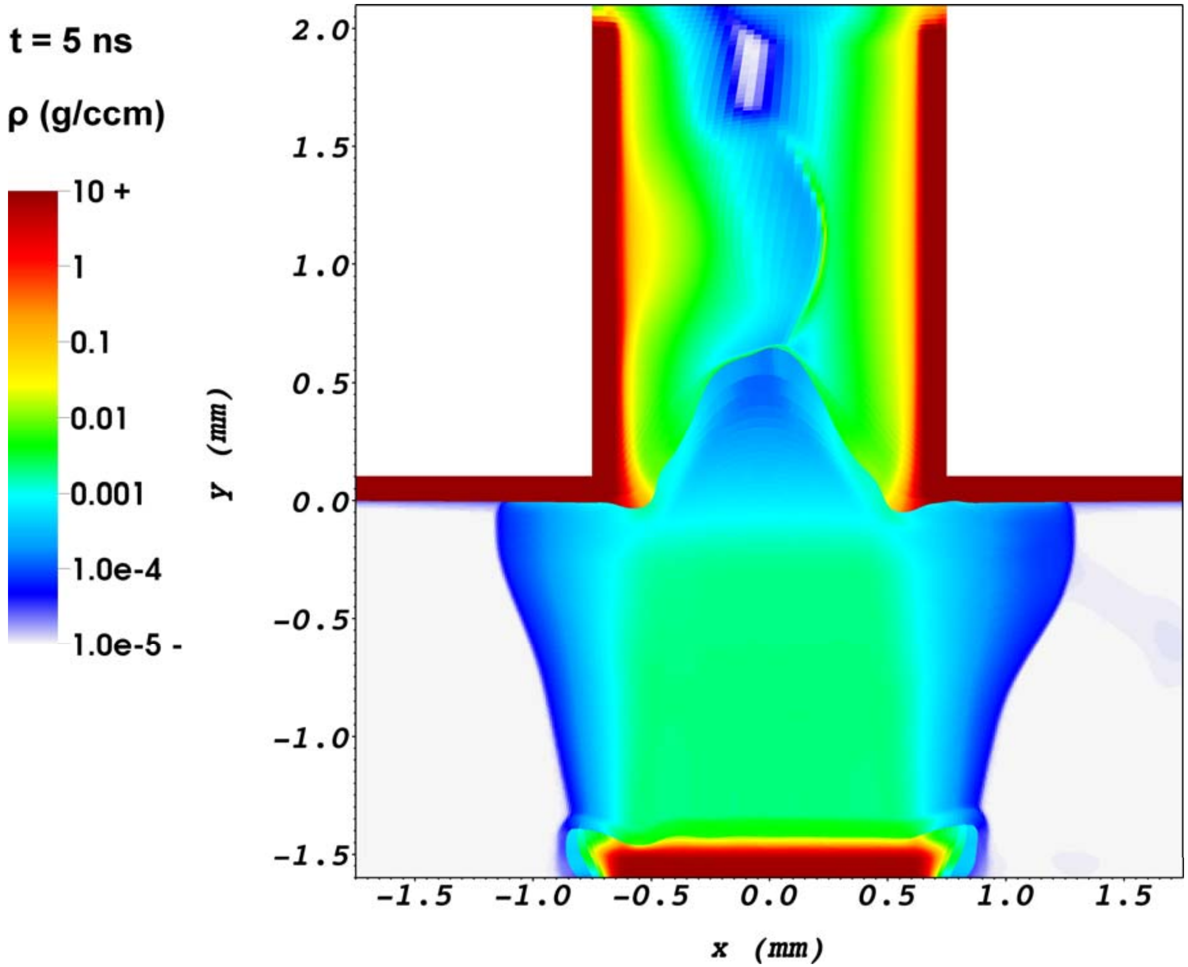
Plasma heating by hohlraum radiation (4)

ρ, g/cm^3



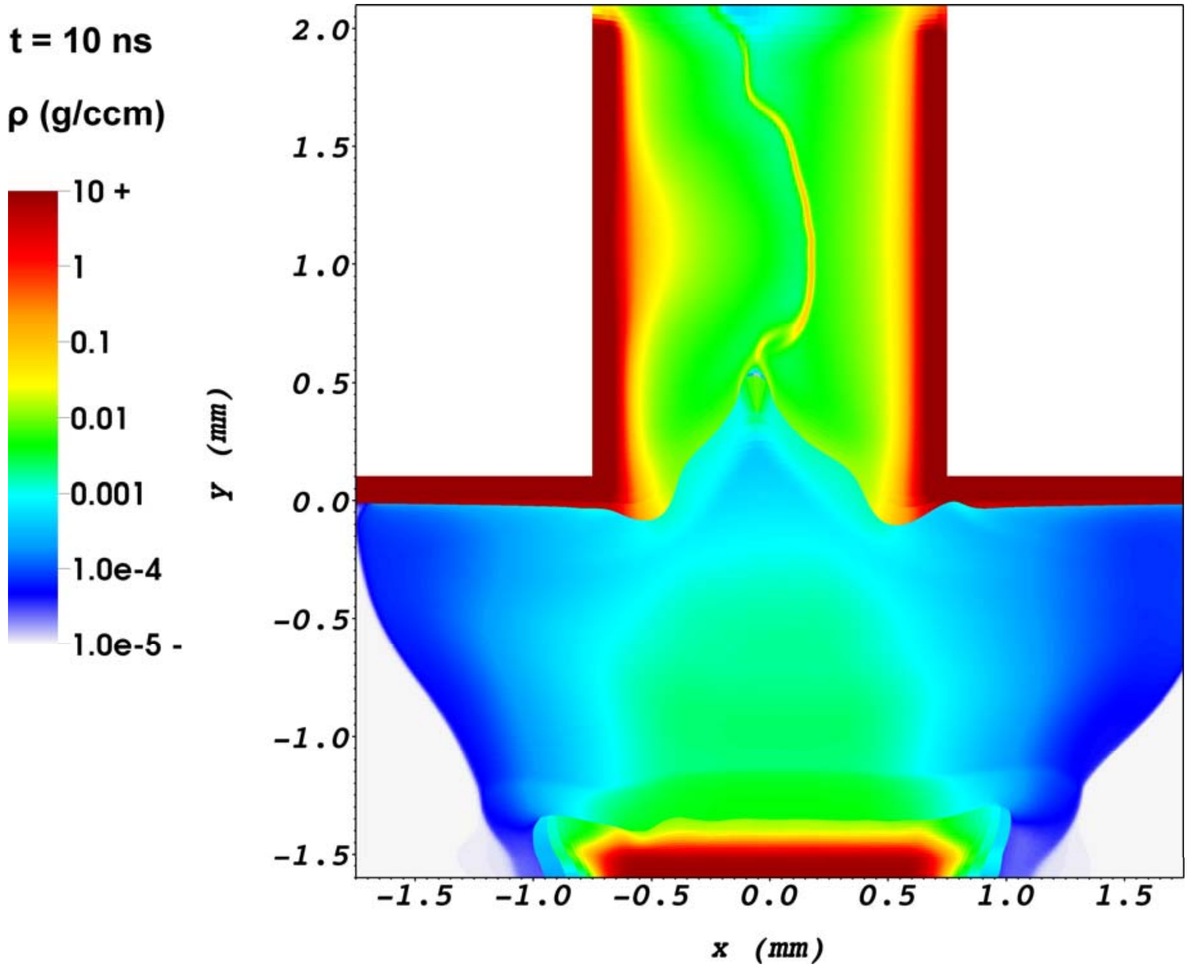
Plasma heating by hohlraum radiation (4)

ρ, g/cm³



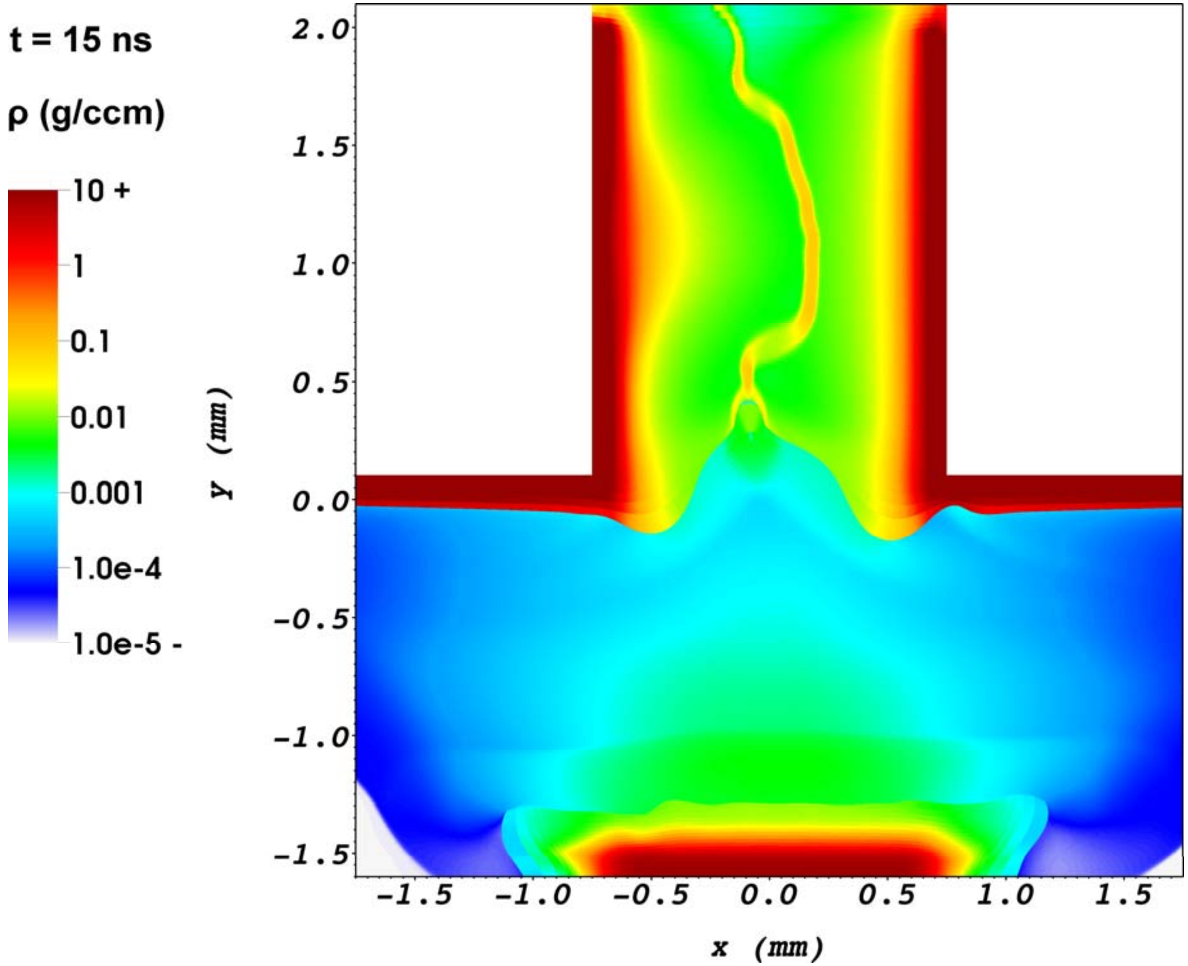
Plasma heating by hohlraum radiation (4)

ρ, g/cm³



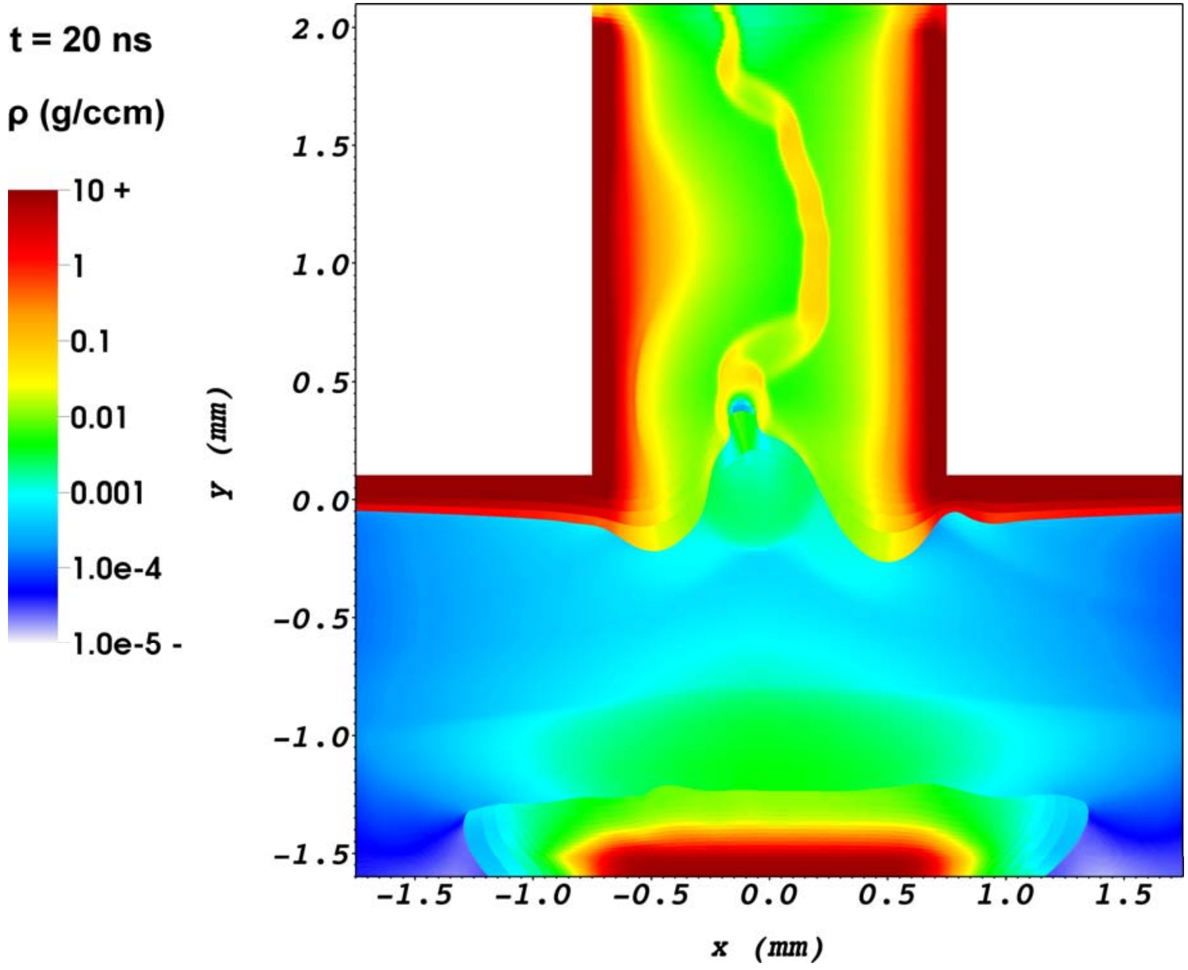
Plasma heating by hohlraum radiation (4)

ρ, g/cm^3



Plasma heating by hohlraum radiation (4)

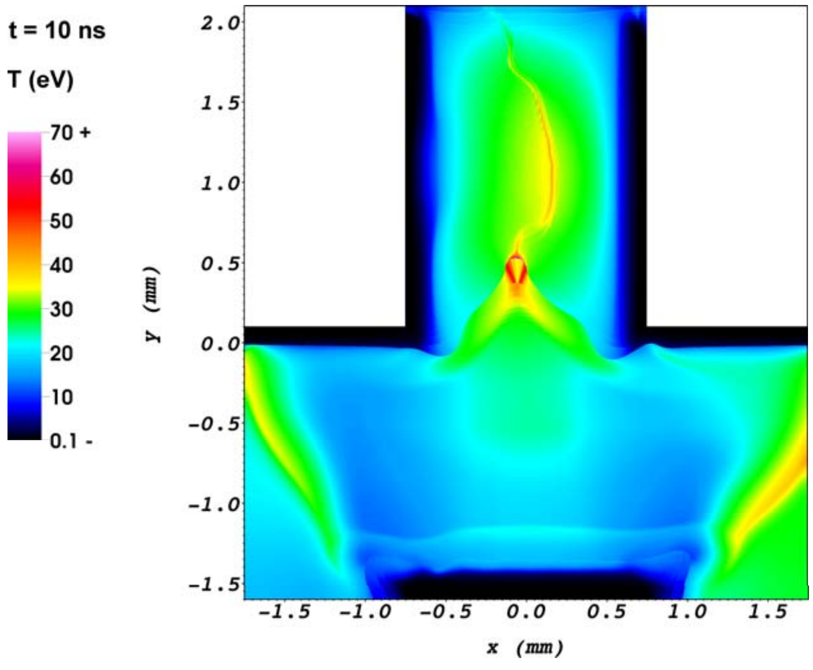
ρ, g/cm^3



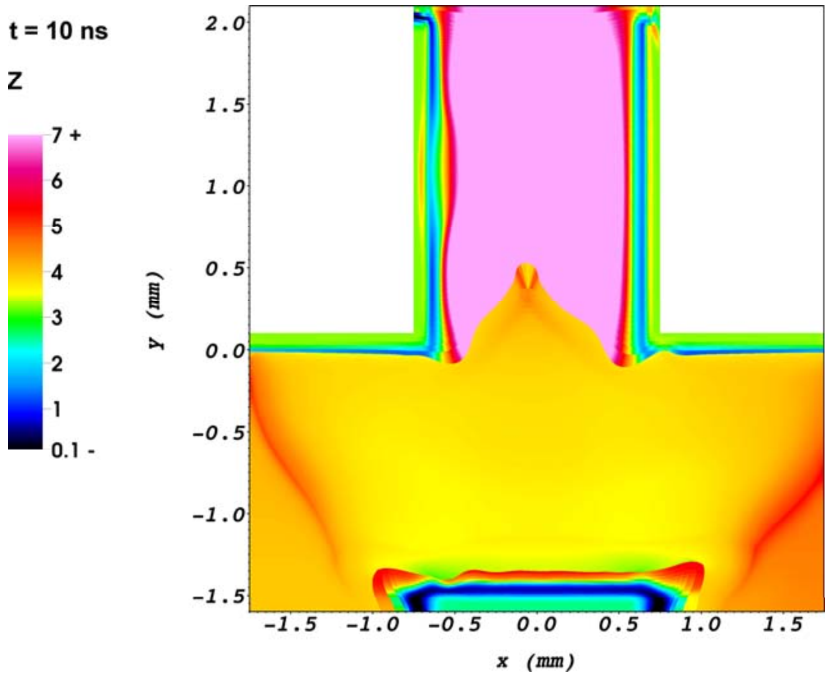
Plasma heating by hohlraum radiation (5)

Plasma temperature, T and ionization degree, Z at t = 10 ns

T, eV



Z

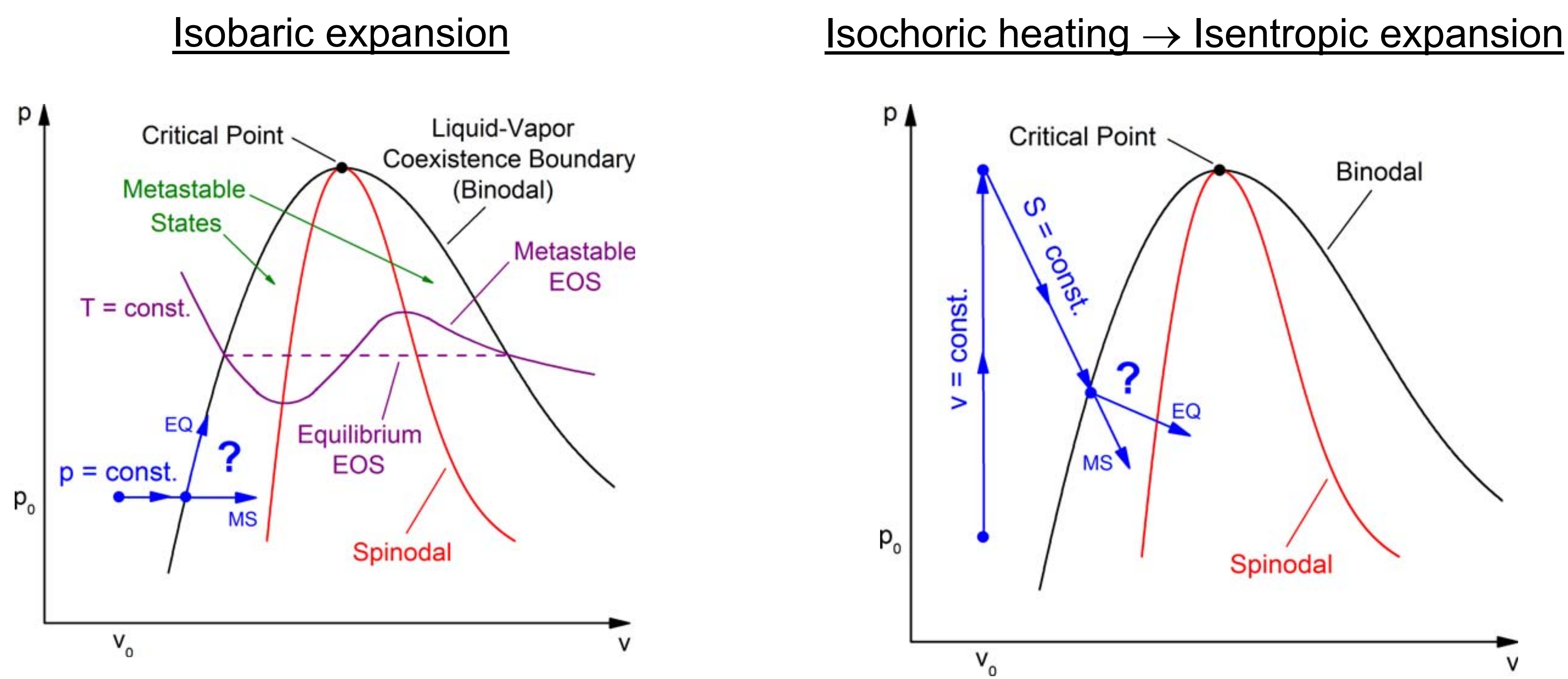


- Indirect plasma heating by means of hohlraum radiation allows to create a uniform plasma state of partially ionized carbon ($Z \approx 3.8$) at temperatures $T \approx 20$ eV.
- Shock wave from the foam support can be eliminated by slight change of the setup.

Warm Dense Matter Regime

General problem in hydrodynamic simulations

In the metastable region between the binodal and spinodal we have a double-valued EOS !



Dilemma: which of the two should one follow in hydrodynamic simulations?

Our recipe: follow metastable EOS and use the criterion for explosive boiling

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Local criterion of explosive boiling

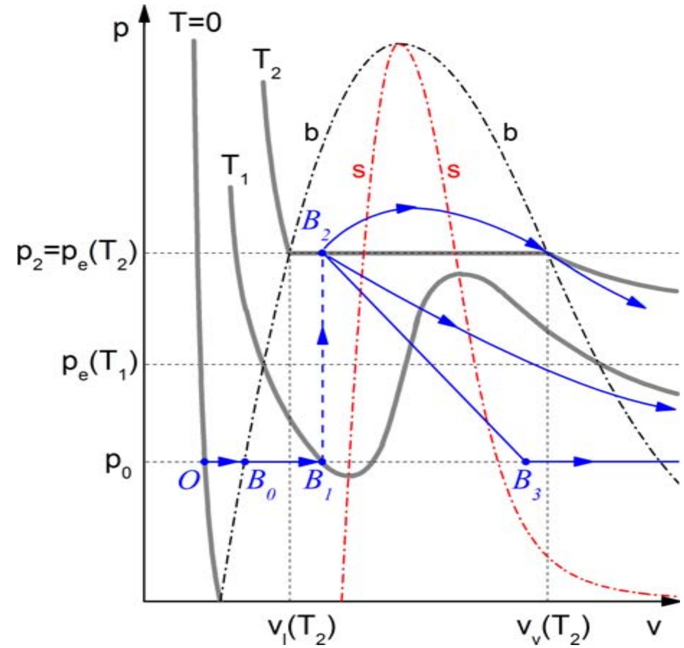
Theory of homogeneous bubble nucleation:

Rate of spontaneous bubble creation

$$J = N\left(\frac{3\sigma}{\pi m}\right)^{1/2} \exp\left(-\frac{W_c}{T}\right) \quad [\mathrm{cm}^{-3}\mathrm{s}^{-1}]$$

W_c – work of the bubble formation, σ - surface tension

Isobaric expansion



Proposed (local) criterion of explosive boiling:

$$\int_0^t J(t')V(t')dt' \overset{!}{=} \xi_v \,,$$

$$\xi_v \equiv \frac{\rho_l(T_2)-\rho}{\rho_l(T_2)-\rho_v(T_2)}$$

Total fractional volume of overcritical bubbles $\overset{!}{=}$ equilibrium value ξ_v

$$NV_c\left(\frac{3\sigma}{\pi m}\right)^{1/2}\left[\frac{d}{dt}\left(-\frac{W_c}{T}\right)\right]_{Lag}^{-1} \exp\left(-\frac{W_c}{T}\right) = \xi_v$$

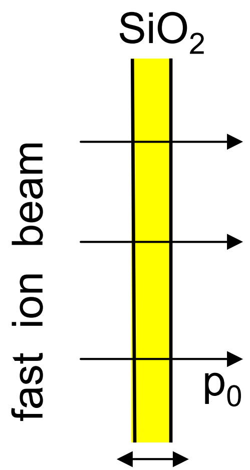
$V_c \equiv \frac{4\pi}{3} r_c^3$, T_2 from $\varepsilon(\rho,T_1) = \varepsilon_{eq}(\rho,T_2)$

The criterion of explosive boiling is fulfilled $\Rightarrow$ Instantaneous irreversible transition to the equilibrium EOS at fixed density and specific internal energy ($B_1 \rightarrow B_2$).

GSI

Application to a uniform planar layer of SiO_2

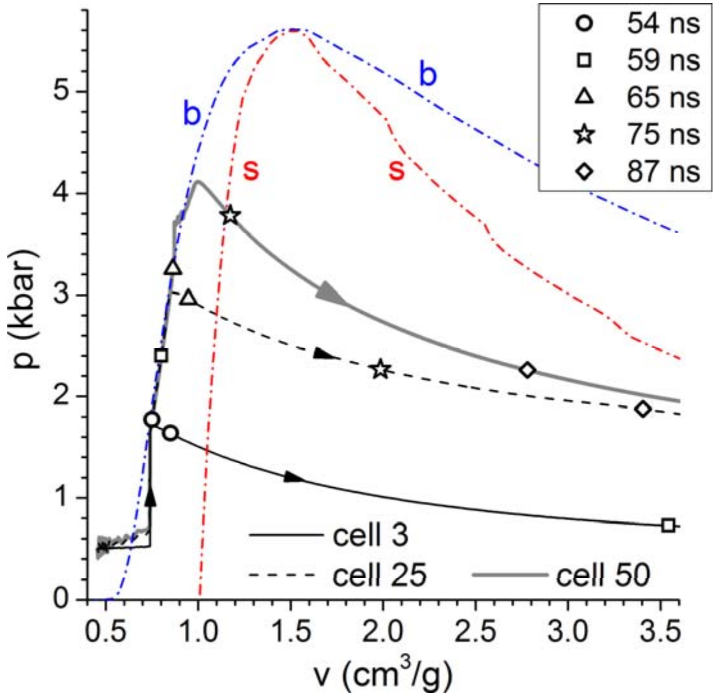
Example: thin SiO_2 foil heated quasi-isobarically by the ion beam (spatially uniform ρ, p, T)



l=10 μm, 100 Lagrangian cells

$q = 10^{11}$ J g^{-1} s^{-1}

v – p phase plane



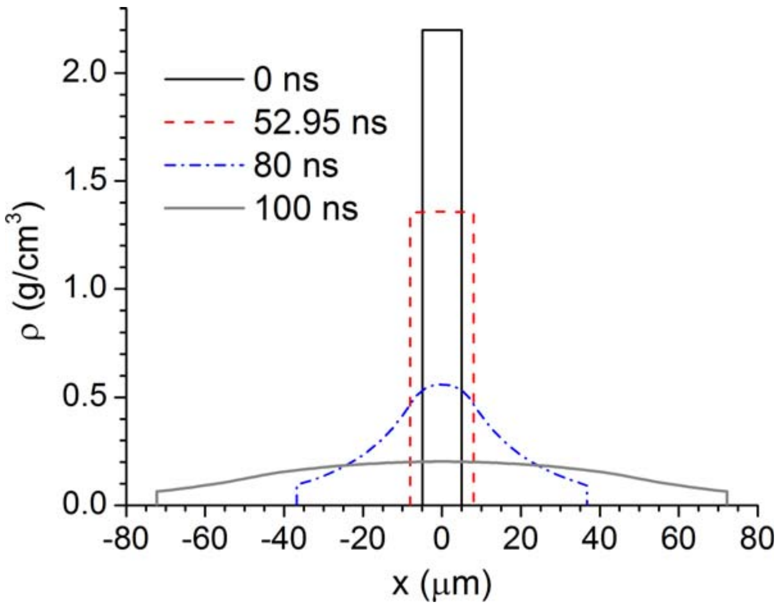
Start with metastable EOS → switch to equilibrium EOS at t_b = 52.95 ns (3923 K)

Evolution after boiling:

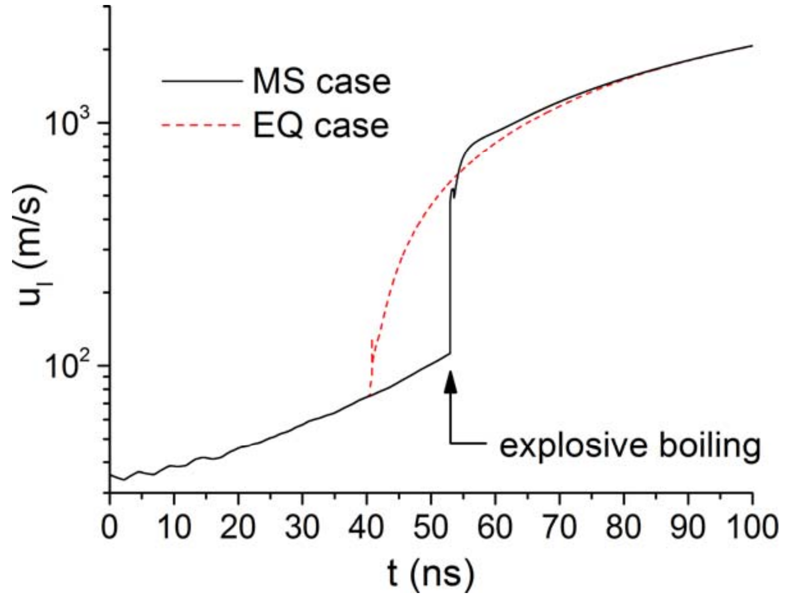
- The boundary relaxes to p_0
- The center elements follow for about 20 ns the binodal until the rarefaction wave arrives (c_s drops strongly, $c_{s2}/c_{s1} < 0.1$)

Application to a uniform planar layer of SiO_2 (2)

Density profiles



Surface velocity



$t \leq t_b$: ρ homogeneous
$t > t_b$: $\rho \approx$ Gaussian

Strong jump in u_l at $t = t_b$, which should be measurable at the experiment !

Adequate modeling of the explosive boiling is indispensible for planning and interpretation of experiments in the two-phase liquid-vapor region.

S. Faik, M. Basko, An. Tauschwitz, I. Iosilevskiy, J. Maruhn, HEDP **8** (2012) 349.

Conclusions

- RALEF-2D has become a powerful radiation hydrodynamics code in terms of speed, accuracy and variety of solvable problems.

- Wide range of problems regarding radiation-dominated plasmas can be addressed using RALEF-2D.

- A solution for the double-valued EOS in the two-phase region has been worked out which is prerequisite for reliable hydrodynamic simulations in the WDM regime.