Radiation hydrodynamic simulations of $\lambda = 2$ μm laser irradiation of tin microdroplets

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Outline of the talk

- Motivation for this session
- Problem statement:

λ = 2 μm laser irradiation of tin microdroplets and/or slab targets.

- RALEF-2D code and results
- Conclusion and outlook

Code comparison and validation

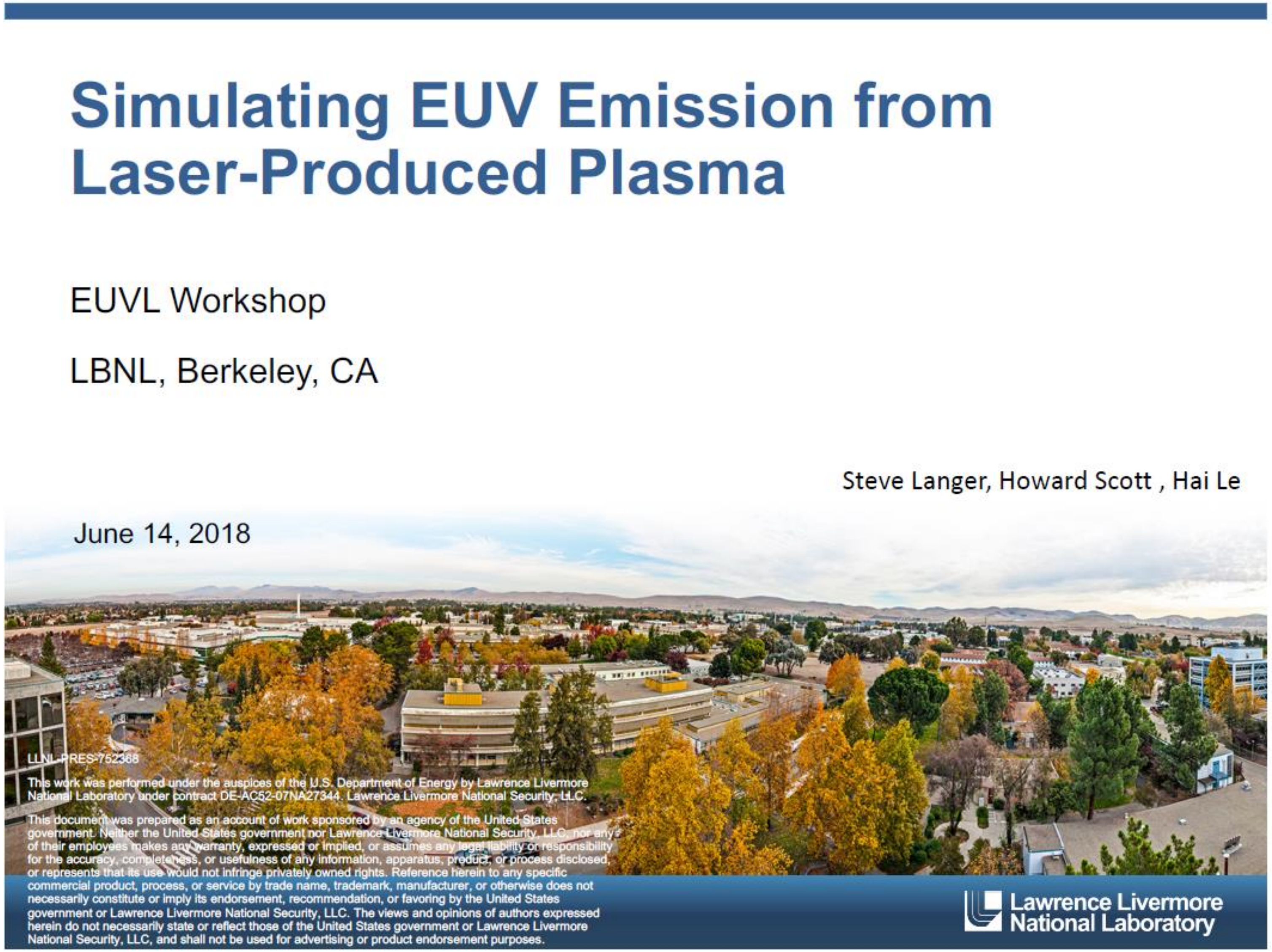
Motivation: Provide a platform with which simulation results can be compared for a well-defined problem.

Meeting	Year	Location	Results
NLTE-1	1996	Gaithersburg, MD, USA	Lee et al, JQSRT **58**, 737 (1997)
NLTE-2	2001	Virtual Workshop	Bowen et al, JQSRT **81**, 71 (2003)
NLTE-3	2003	Gaithersburg, MD, USA	Bowen et al, JQSRT **99**, 102 (2005)
			Rubiano et al, HEDP **3**,

Treatment of **dielectronic recombination (DR)** process greatly affects ion population distributions

Discussion session – your input is very much appreciated!!

Problem motivation



<u>LLNL is developing solid-state lasers</u>

Thulium laser (λ = 1.9 μm) is one such example.

- Average power ≈ 300 kW.
- Pulse-to-pulse jitter < 1%.
- Excellent temporal shaping capabilities.

Key points:

1. 'Does this help or hurt conversion efficiency?'

2. 'Simulations can be used to assess the potential of thulium lasers without the expense of building and fielding one.'

Plasma generation with λ = 2 µm laser

Critical electron density set by laser wavelength according to

$$n_{ec} = 10^{21}/\boldsymbol{\lambda^2} \text{ cm}^{-3}$$

$n_{ec,\mathbf{1.06\ \mu m}} \approx 10^{\mathbf{21}}$ cm^{-3} - Dense, optically **thick** plasma (Nd:YAG).

$n_{ec,\mathbf{10.6\ \mu m}} \approx 10^{\mathbf{19}}$ cm^{-3} - Optically **thin** plasma (CO_2).

$$n_{ec,\mathbf{2\ \mu m}} \approx 3 \text{ x } 10^{\mathbf{20}} \text{ cm}^{-3}$$

- How do electron density profiles vary over time?
- Where is the critical surface?
- Electron temperature distributions? Radiation transport?...

Problem statement

λ = 2 μm laser irradiation of tin microdroplets and/or slab targets

Simulation parameters:
- λ = 2 μm
- Droplet diameter: **25 μm** and 50 μm
- Temporal profile: Box shape, **10 ns** duration
- Spatial profile: Gaussian having a beam waist ($1/e^2$) of **100 μm**
- Laser power densities: **5 - 1**, **0.5**, 0.1 and 0.05 x 10^{10} W/cm^2

Output quantities:
- **Time**- and **space**-dependent *electron* and/or *ion **densities**.*
- **Time**- and **space**-dependent *electron **temperatures**.*
- EUV spectra and conversion efficiencies.

RALEF-2D code

RALEF-2D solves the single-fluid, single-temperature hydrodynamic equations in two dimensions (x-y or **r-z** geometry)

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

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

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

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

ideal hydrodynamics

coupling with the radiation field

M. M. Basko, J. A. Taruhn, and A. Tauschwitz, "Development of a 2D radiation hydrodynamics code RALEF for laser plasma simulations," GGSI Report 2010-1 PLASMA-PHYSICS-25 (GSI Helmholtzzentrum für Schwerionenforschung GmbH, 2010)

$\nabla \cdot \left(\kappa \nabla T \right)$ Thermal conduction

Q_r Radiation

Q_{dep} External heating sources

RALEF-2D code: Equation of State

Frankfurt Equation of State

Contents lists available at ScienceDirect

Computer Physics Communications

journal homepage: www.elsevier.com/locate/cpc

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The equation of state package FEOS for high energy density matter[☆]

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Check for updates

Can model (i) **high-temperature** plasma states and
(ii) **low-temperature** liquid-gas phase coexistence region.

RALEF-2D code: Radiation transfer and opacities

Energy transport **via radiation** is modelled using the steady-state radiation transfer equation

k_υ: Absorptivity

$$\mathbf{\Omega} . \nabla I_\upsilon = k_\upsilon (B_\upsilon - I_\upsilon)$$

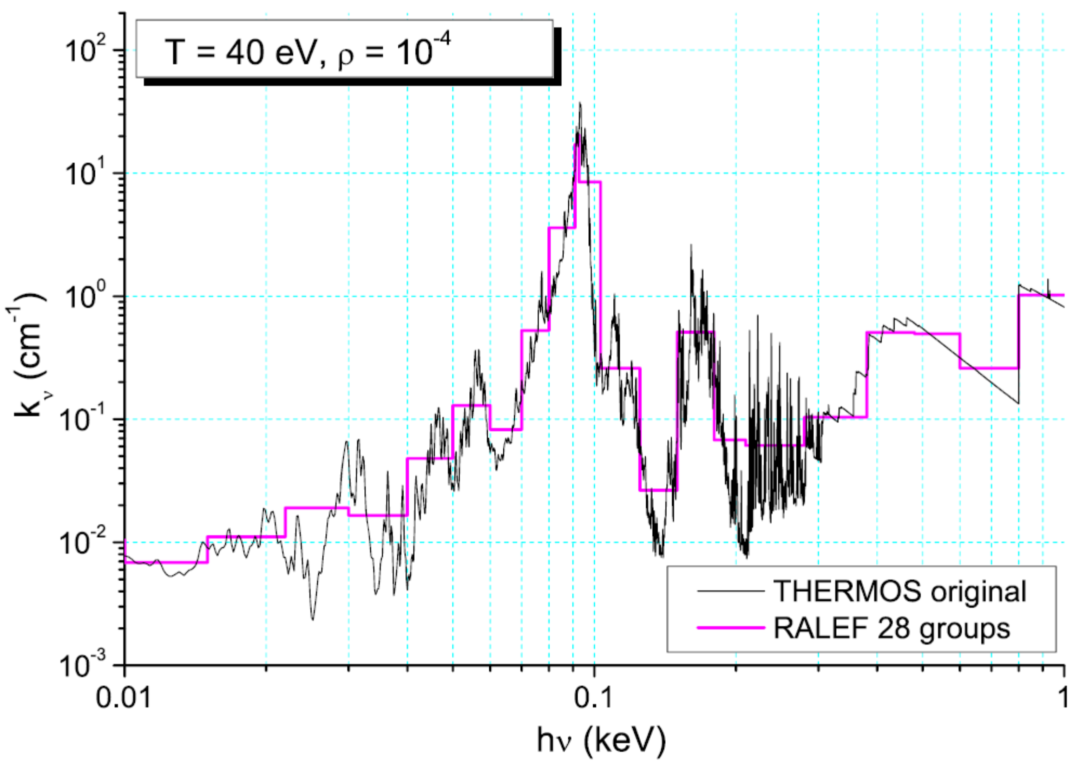
B_υ: Spectral intensity of a blackbody radiator (Plank)

I_υ: Spectral radiation intensity

Opacity tables: **THERMOS** package

k_υ calculated for each (ρ, T) pair by solving steady-state collisional-radiative rate equations.

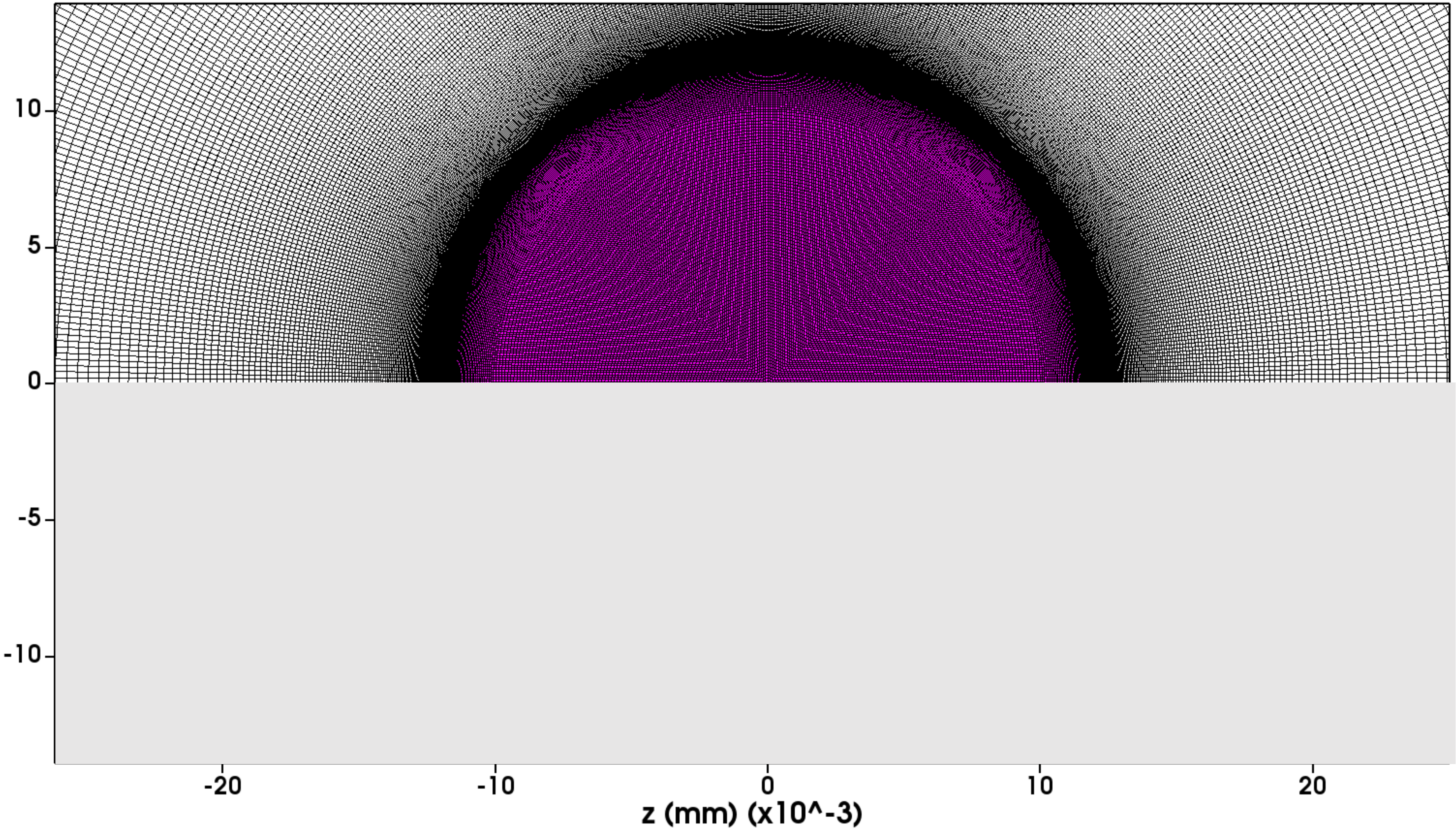
M. M. Basko, Phys. Plasmas **23**, 083114 (2016)
M. M. Basko, V. G. Novikov, and A. Grushin Phys. Plasmas **22**, 053111 (2015) (2016)
A.F. Nikiforov, V. G. Novikov, and V. B. Uvarov, *Quantum-Statistical Models of Hot Dense Matter: Methods for Computation Opacity and Equation of State*
V. G. Novikov et al., High Energy Density Phys. **3**, 198 (2007)



RALEF-2D code: Mesh

Mesh

- 147276 mesh nodes
- Droplet diameter = 25 µm
- ρ = 6.9 g/cc

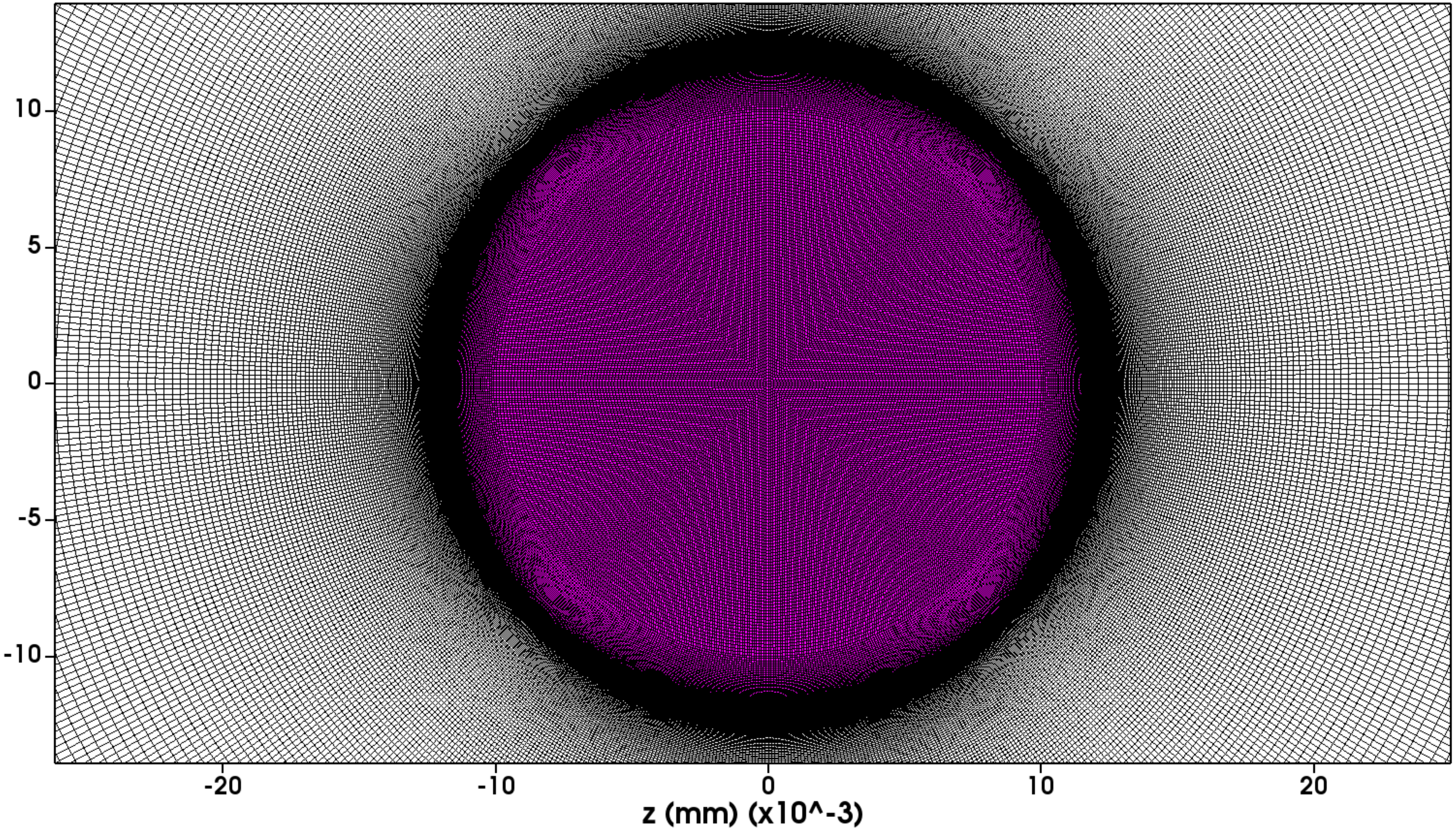


RALEF-2D code: Mesh

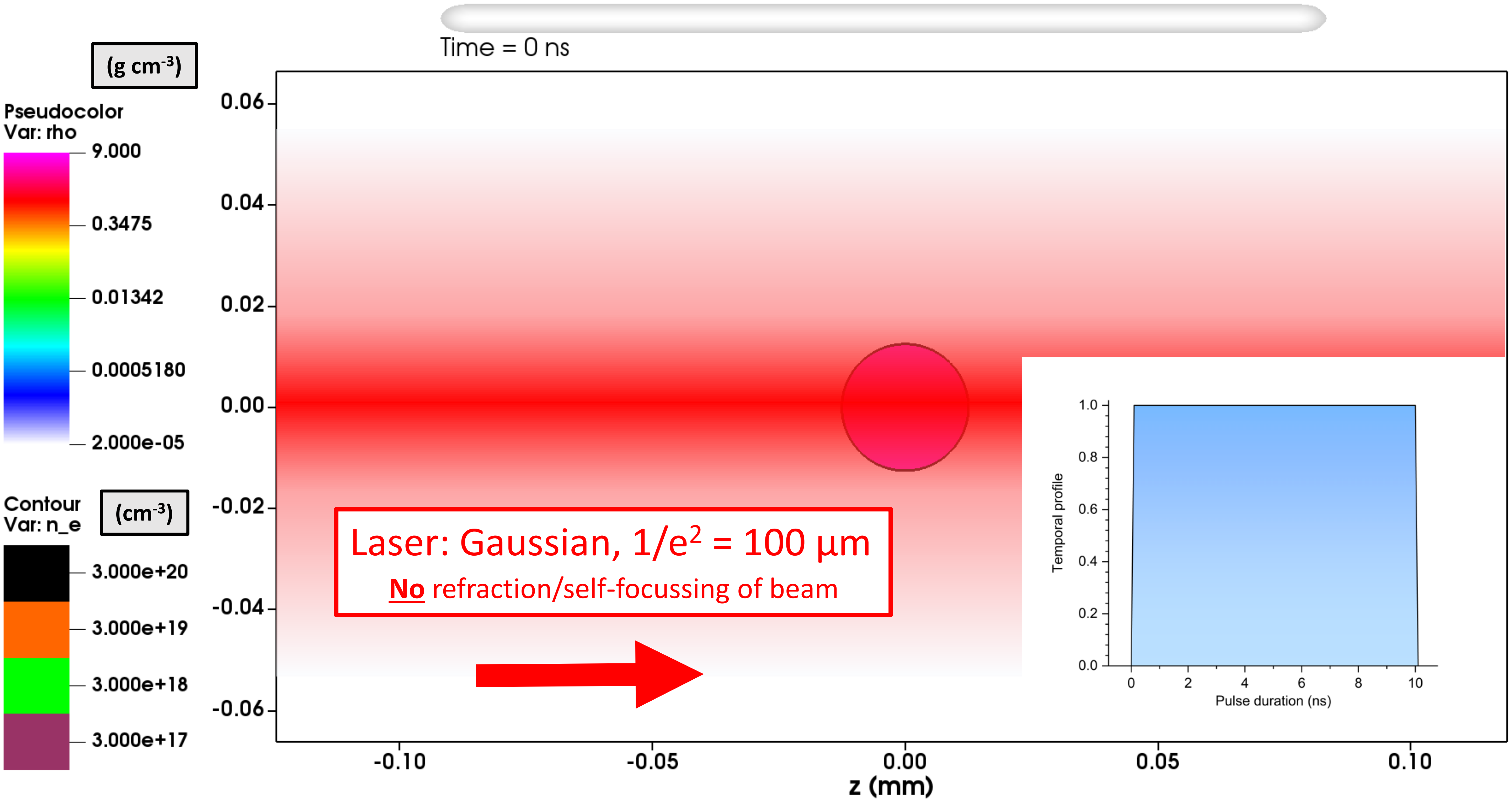
Mesh

- 147276 mesh nodes
- Droplet diameter = 25 µm
- ρ = 6.9 g/cc

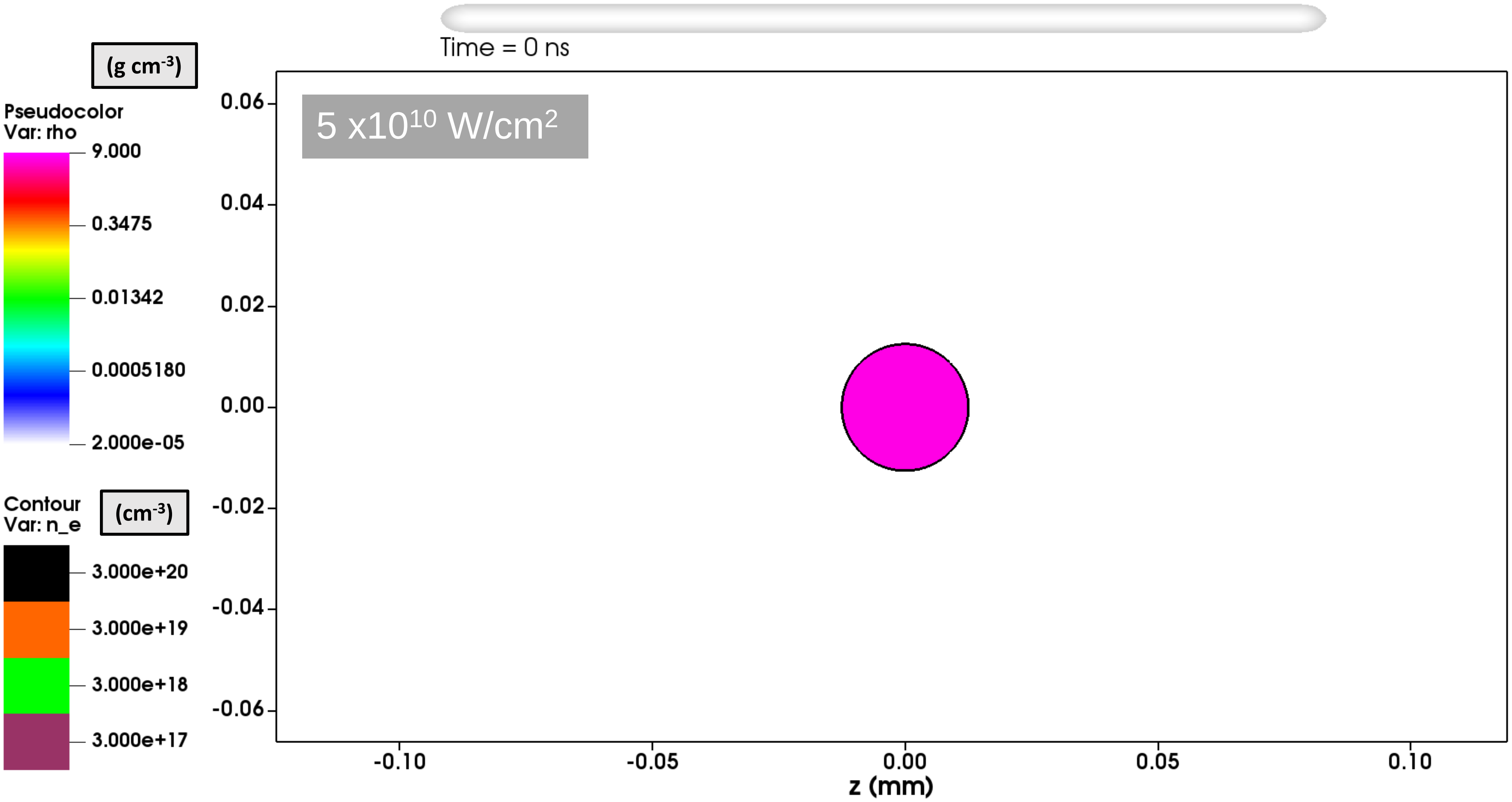
Reflect upper plane to replicate droplet



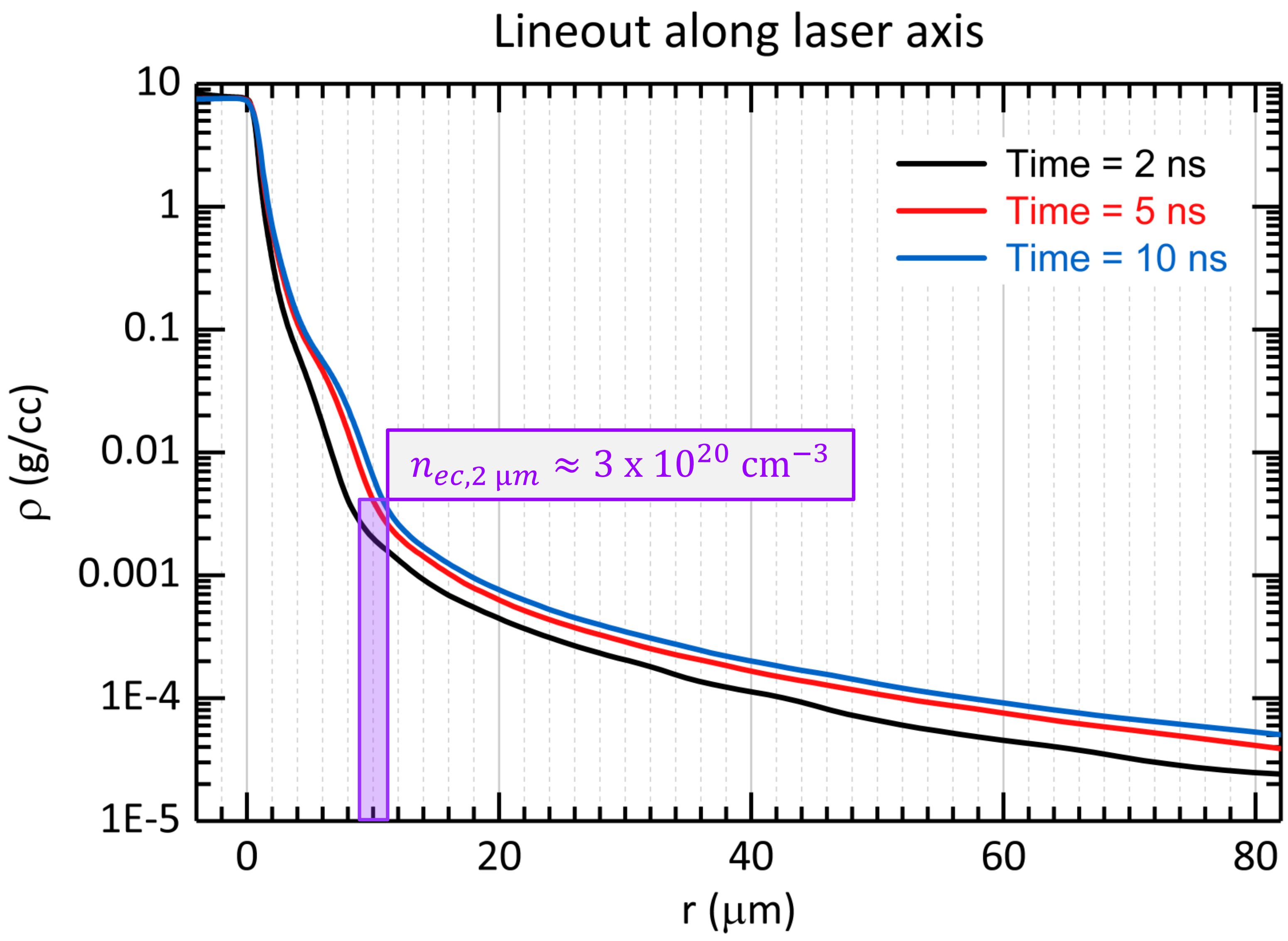
Temporal and spatial variation of ρ, n_e



Temporal and spatial variation of ρ, n_e

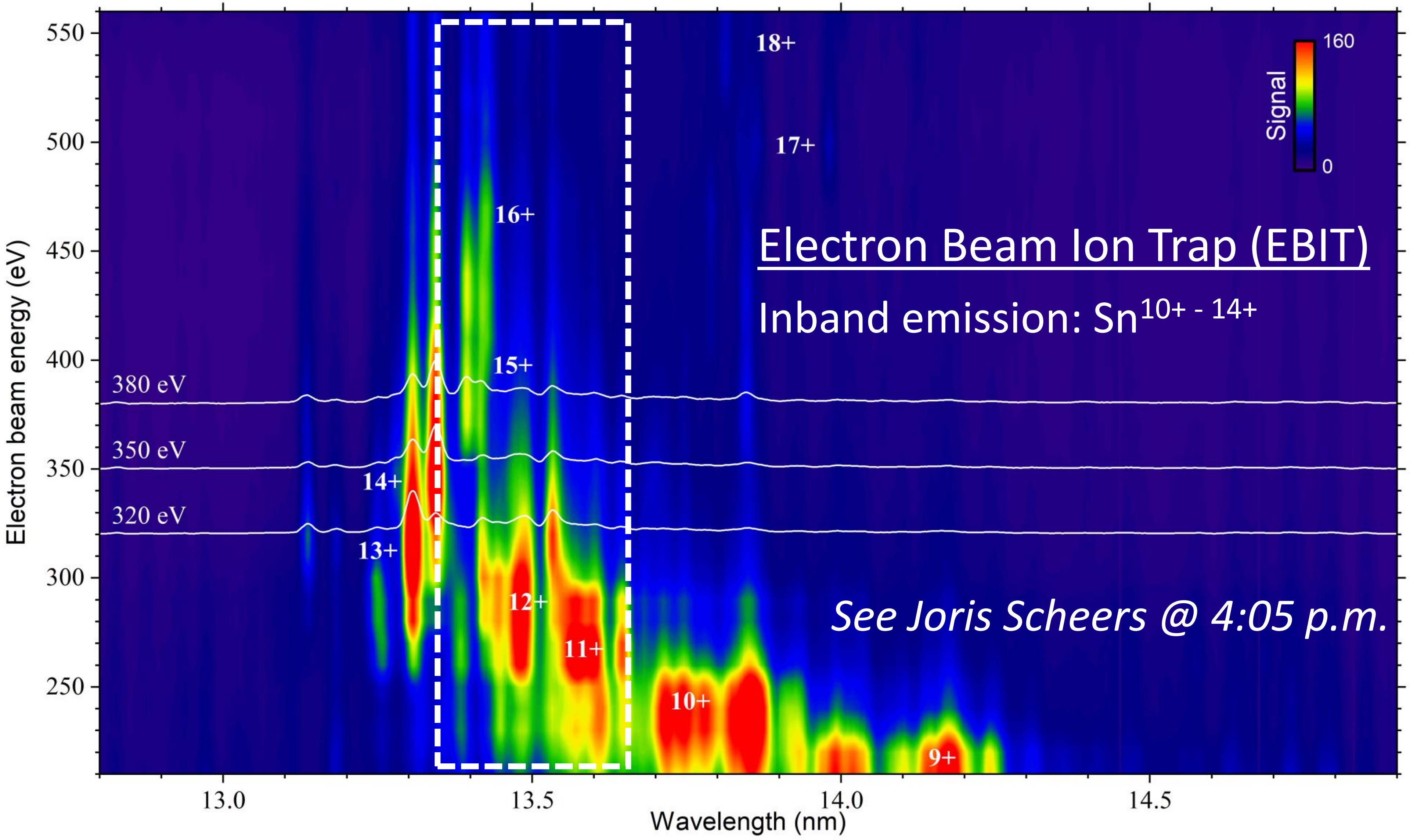


Temporal variation of density

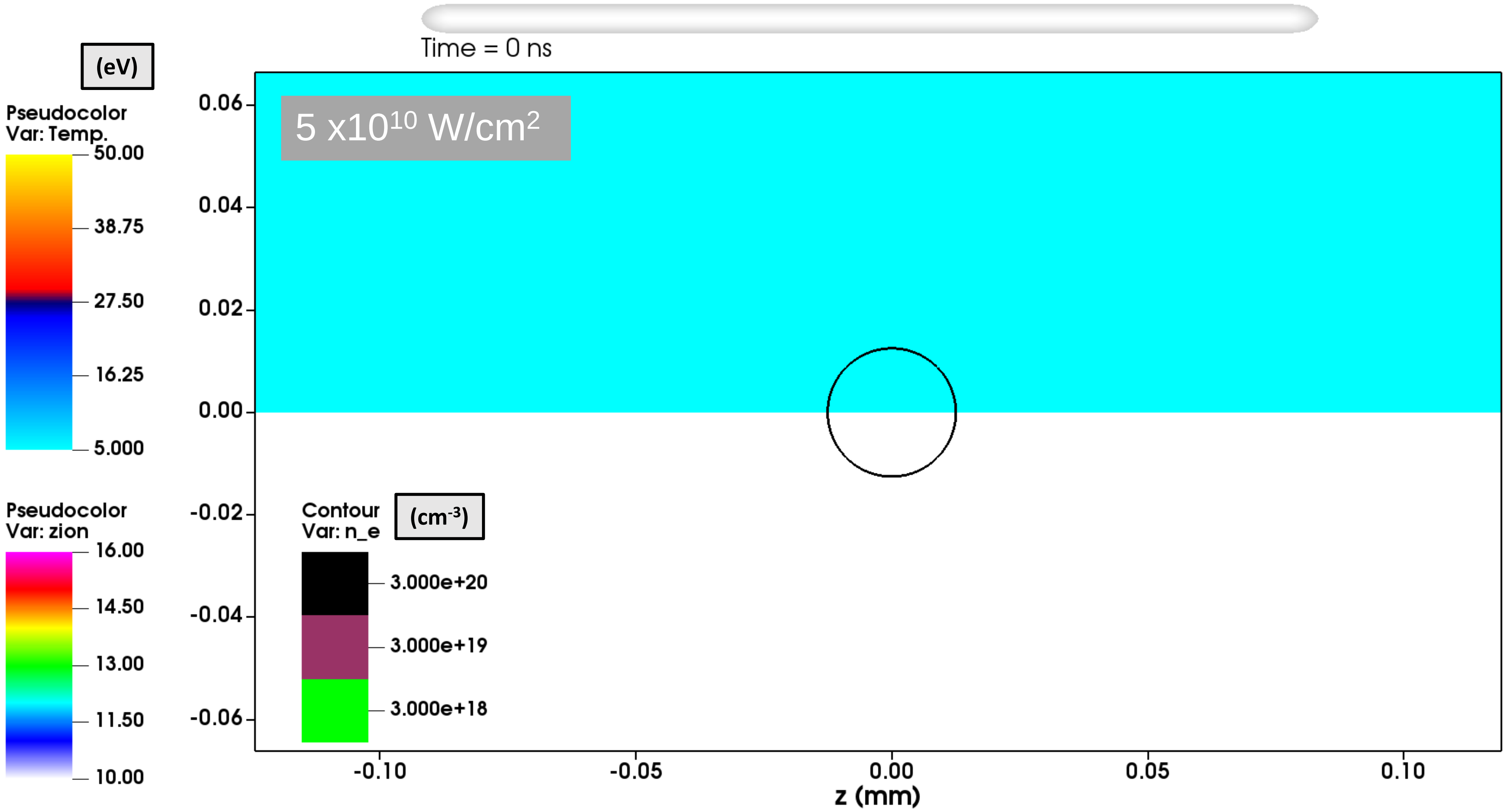


I = 5 x10^{10} W/cm^2

What ions emit inband EUV light?

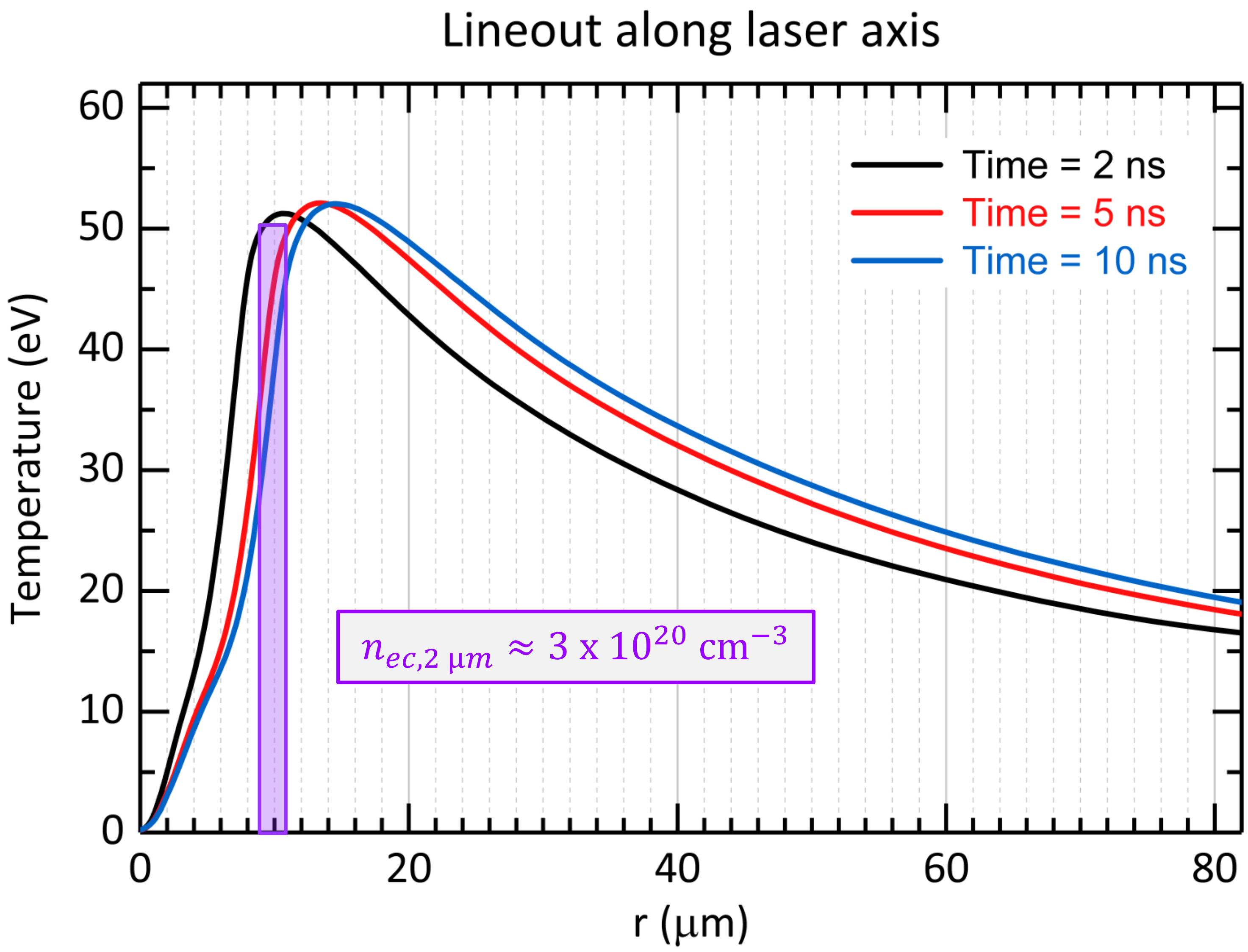


Temporal and spatial variation of T and z_{ion}

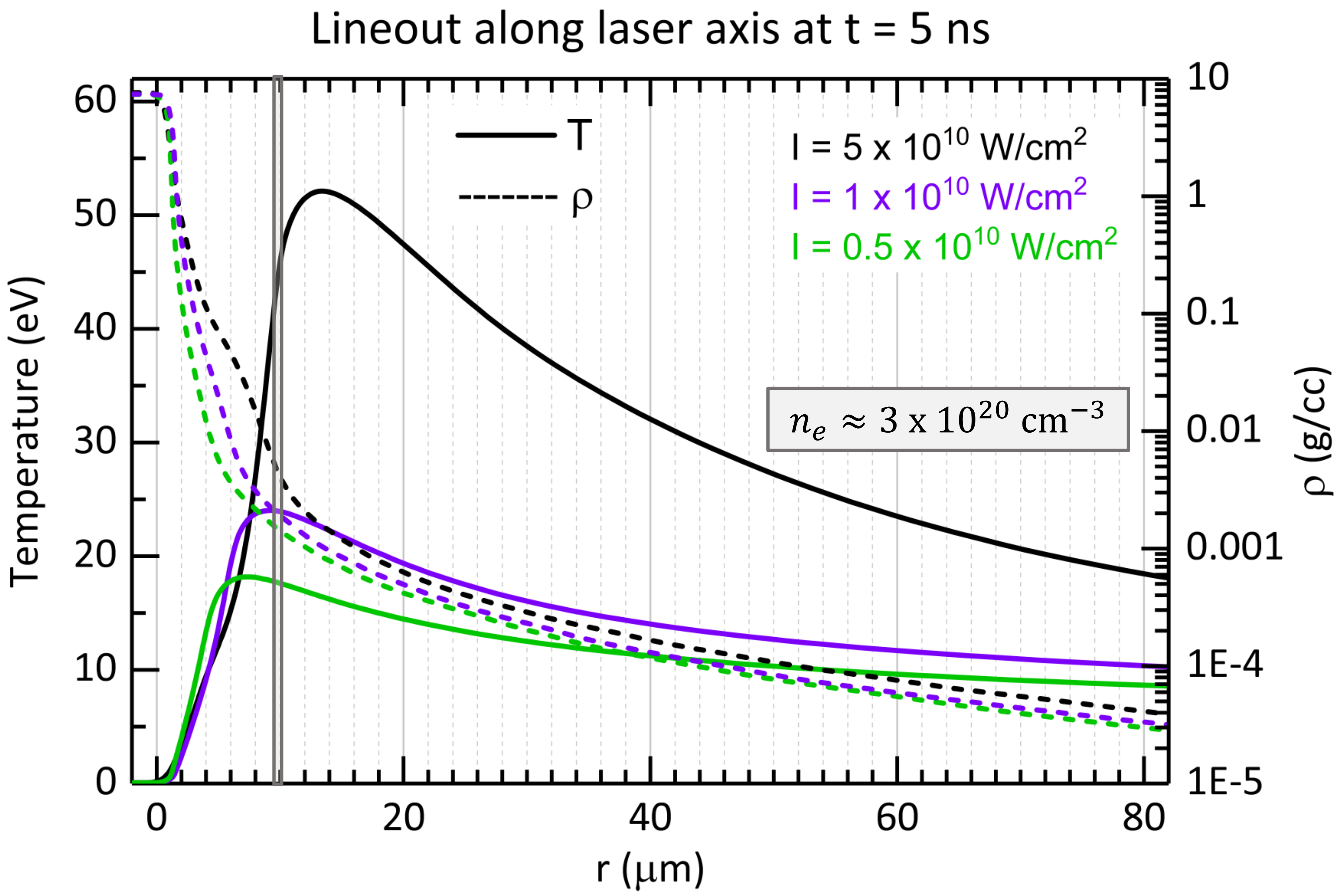


Temporal variation of temperature

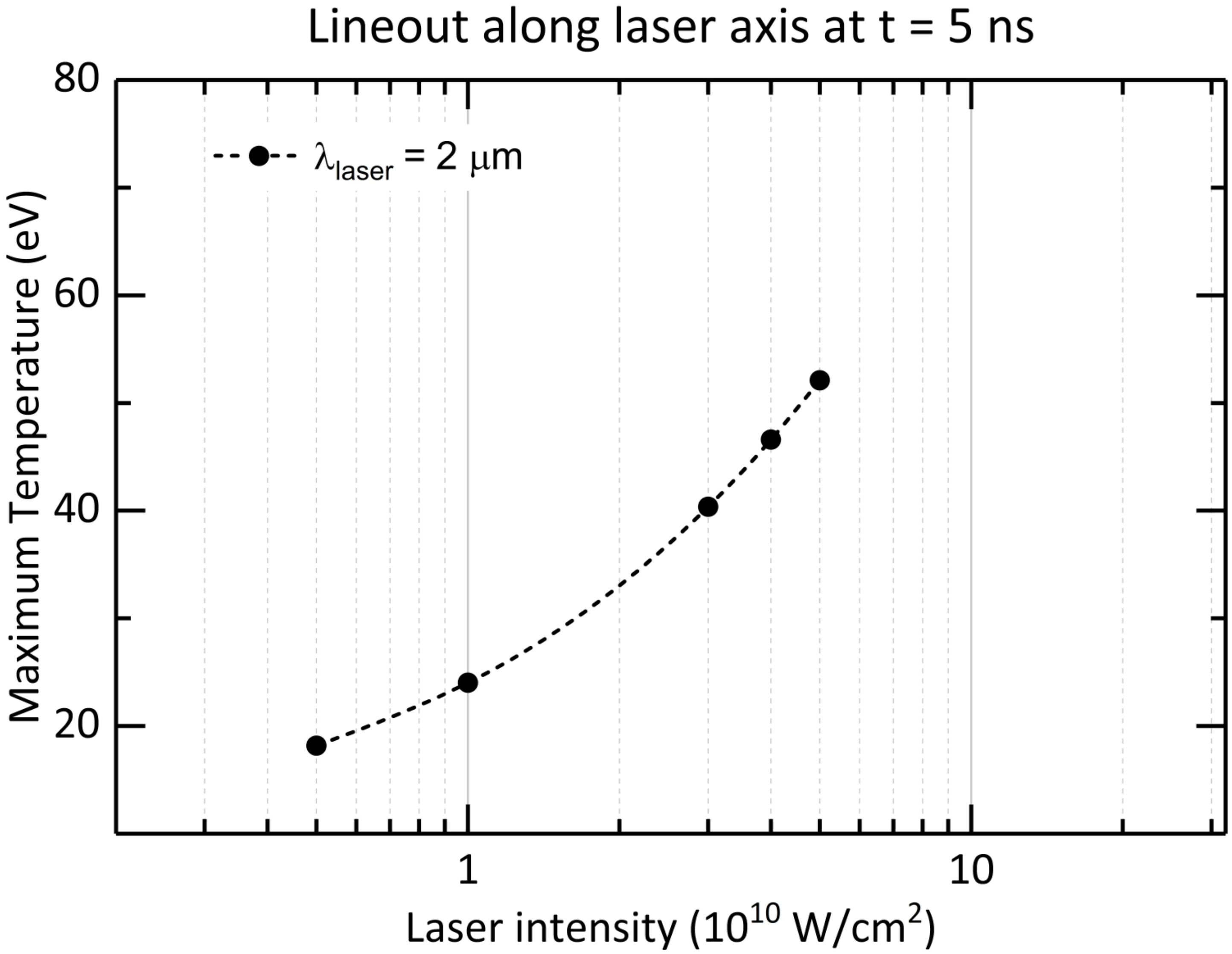
I = 5 x10^{10} W/cm^2



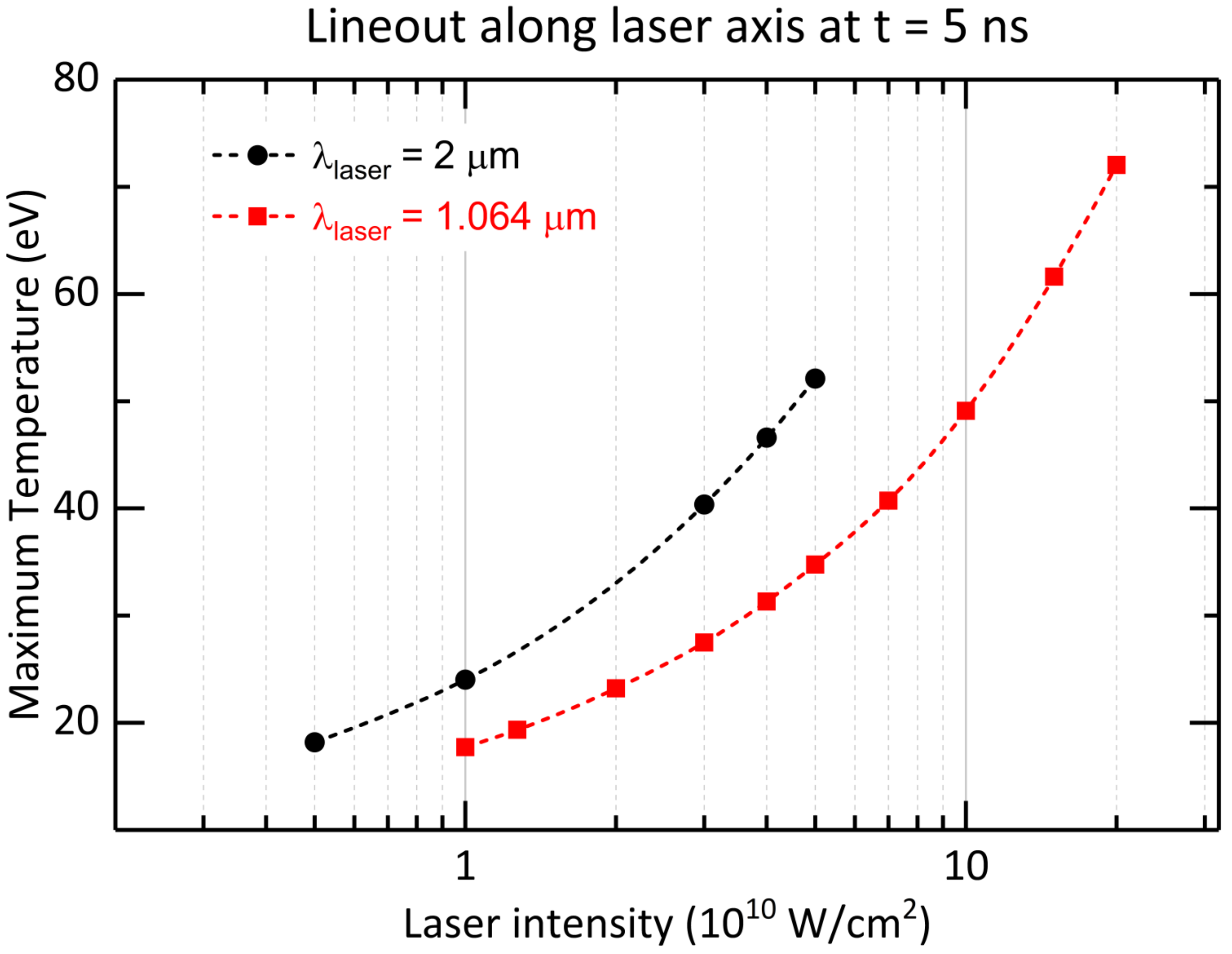
Variation of ρ, T with laser intensity



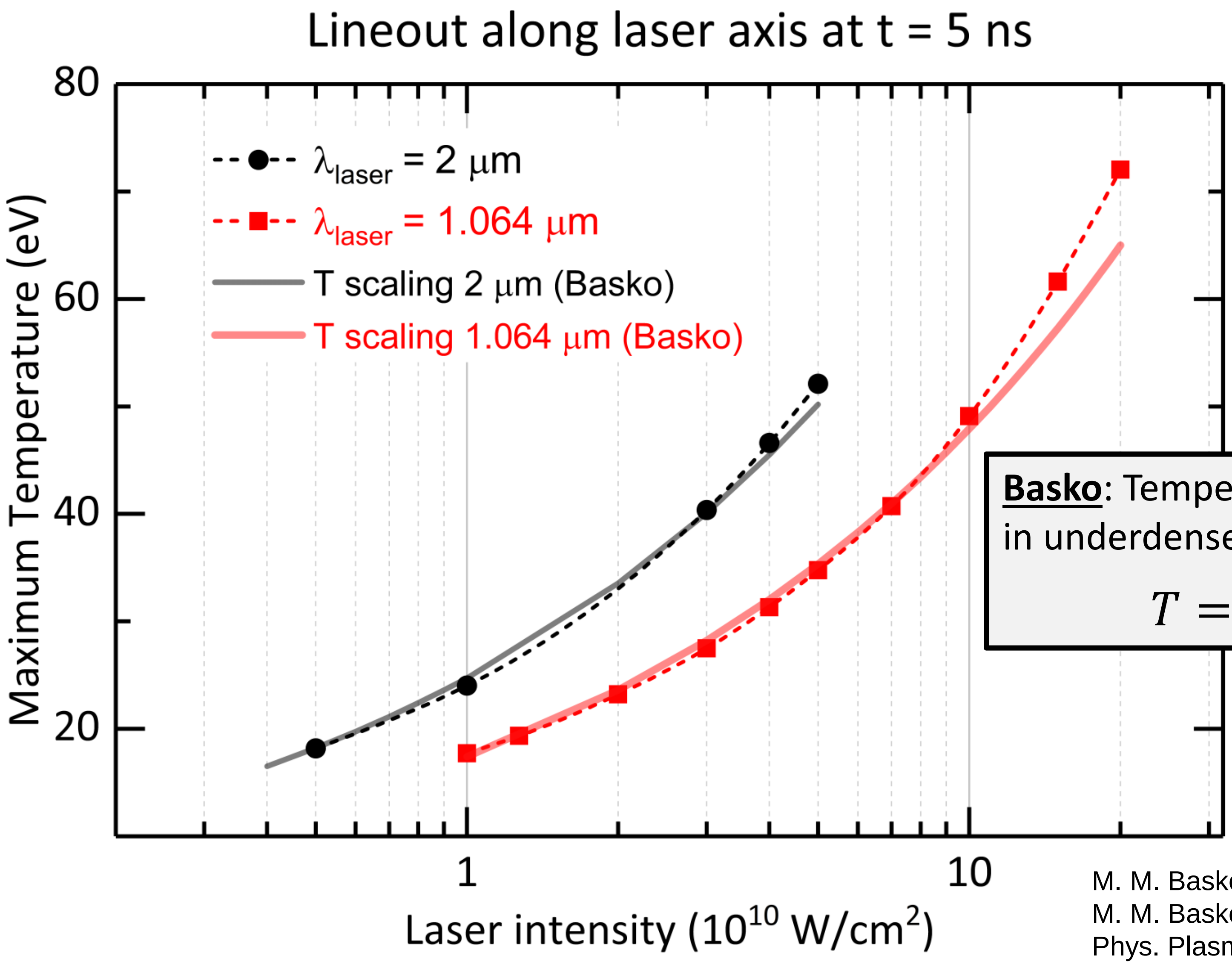
Variation of maximum T with laser intensity



Variation of maximum T with laser intensity



Variation of maximum T with laser intensity



Basko: Temperature scaling for absorption in underdense corona

$$T = M\ R\ \boldsymbol{\lambda}^{0.38} \boldsymbol{I}'^{0.44}$$

Radius of sonic surface

Equation of state parameters

M. M. Basko, Phys. Plasmas **23**, 083114 (2016)
M. M. Basko, V. G. Novikov, and A. Grushin
Phys. Plasmas **22**, 053111
(2015) (2016)

Conclusions and Outlook

Conclusions

1. Undertaken RALEF-2D simulations of λ = 2 µm laser irradiation of a tin microdroplet.
2. Identified variation of (ρ, T) on laser intensities in the range (**0.5** – **5**) x 10^{10} W/cm^2.
3. Comparisons drawn with Nd:YAG (λ = 1.064 µm) case.

Outlook

How will the results depend on:

1. Underlying Equation of State (EOS)?
2. Adopted opacity tables? – *See James Colgan's talk on Tuesday.*

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Thank you for your attention!!

ASML

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