Kinetic study of nanofoam homogenisation under intense laser irradiation

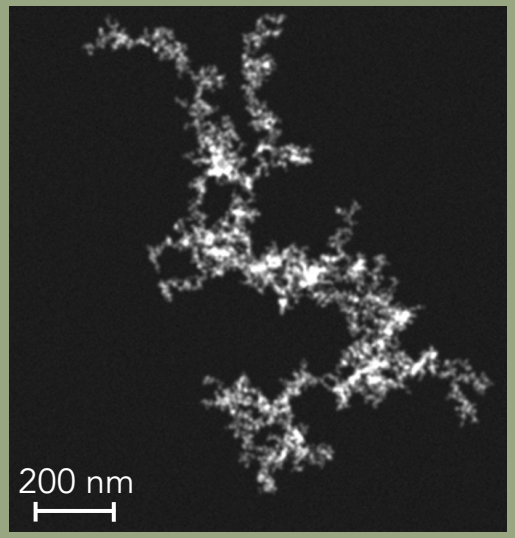
Workshop on micro- and nano-structured materials for experiments with high-power lasers

Kevin Ambrogioni, Claudia Mallimaci, Marta Galbiati, Alessandro Maffini, Mattia Cipriani, Francesco Mirani, Fabrizio Consoli, Matteo Passoni

POLITECNICO MILANO 1863 NanoLab ENEA RSE Ricerca Sistema Energetico CINECA HiPER+ EUROPEAN LASER FUSION ENERGY

Nanofoams for laser-plasma interaction

Nanofoams produced with pulsed-laser deposition (PLD) @ NanoLab



Fractal materials composed of nanoparticle clusters

Mean **density** related to cluster dimension

Talk by Francesco Mirani on 08th of June:
Numerical and experimental activities on nanostructured carbon foams for Inertial Confinement Fusion at Politecnico di Milano

Talk by Maria Sole Galli De Magistris this morning:
Pulsed Laser Deposition for the synthesis of nanostructured materials for high power laser experiments

M. Galbiati *et al.*, *under review at Sci. Rep.* (2026)
A. Maffini *et al.*, *Plasma Phys. Contr.Fusion, 68:035007* (2026)
A. Maffini *et al.*, *App. Surf. Sci., 599:153859* (2022)
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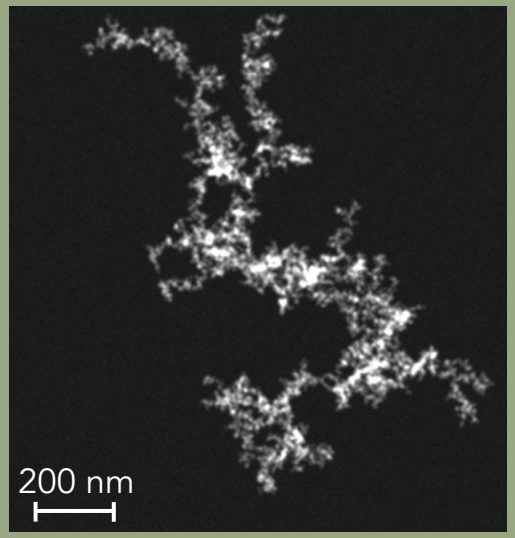

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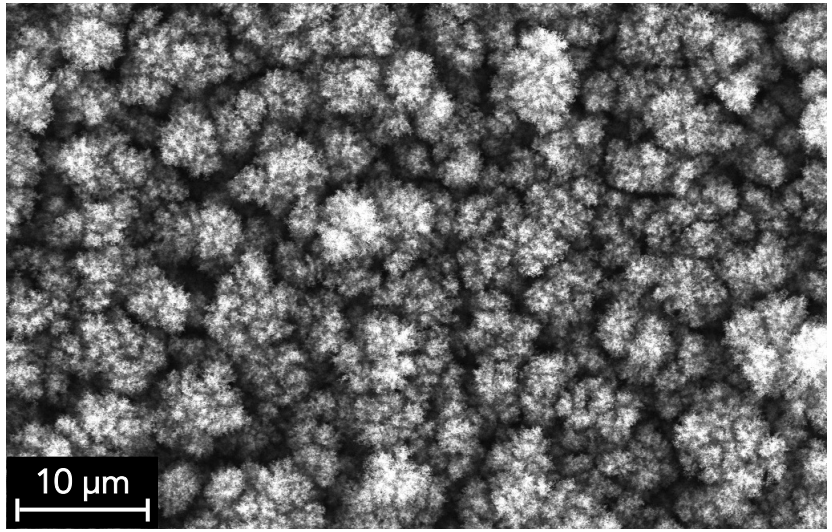
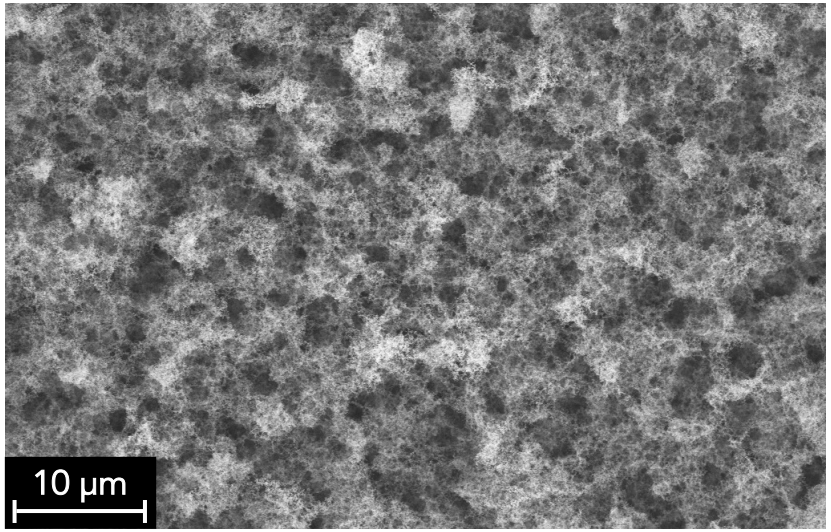


Tree-like carbon foam (26 mg/cm^3)



Web-like carbon foam (8 mg/cm^3)

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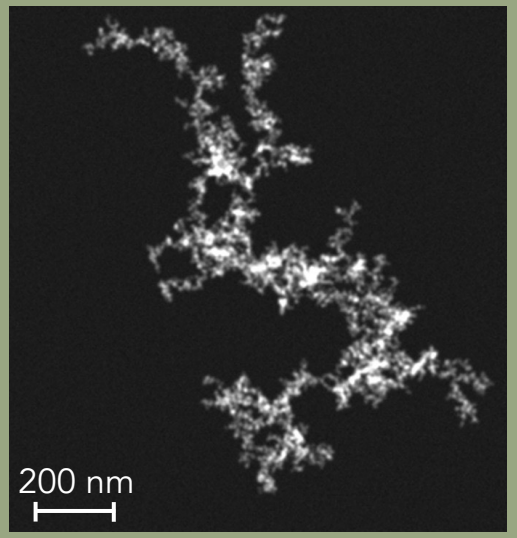

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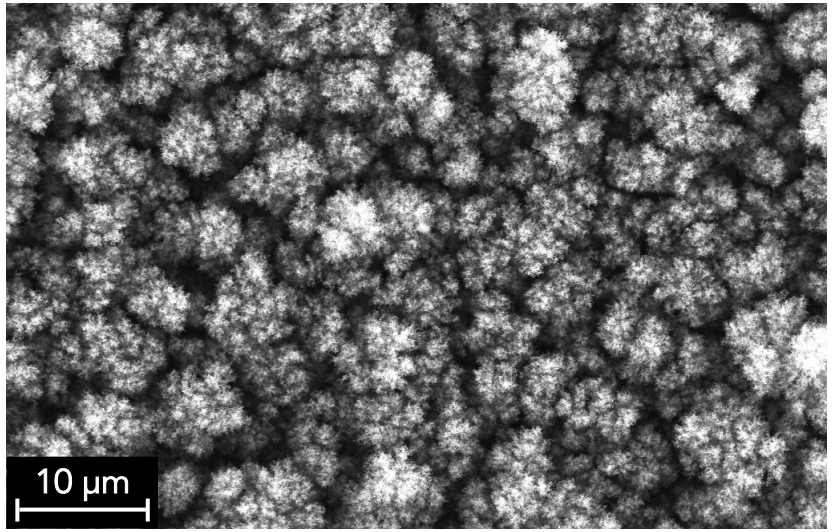

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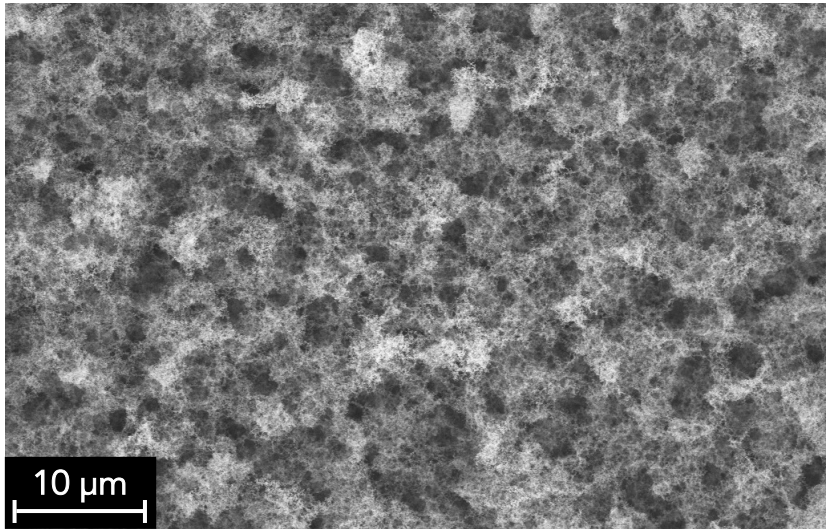

Web-like carbon foam (8 mg/cm^3)

$$\rho_f \sim \rho_{np} N^{-\frac{3-D_f}{D_f}}$$

For **PLD nanofoams** the snowfall-like aggregation process can be simulated via **diffusion-limited cluster-cluster aggregation** (DLCCA, D_f=1.8)

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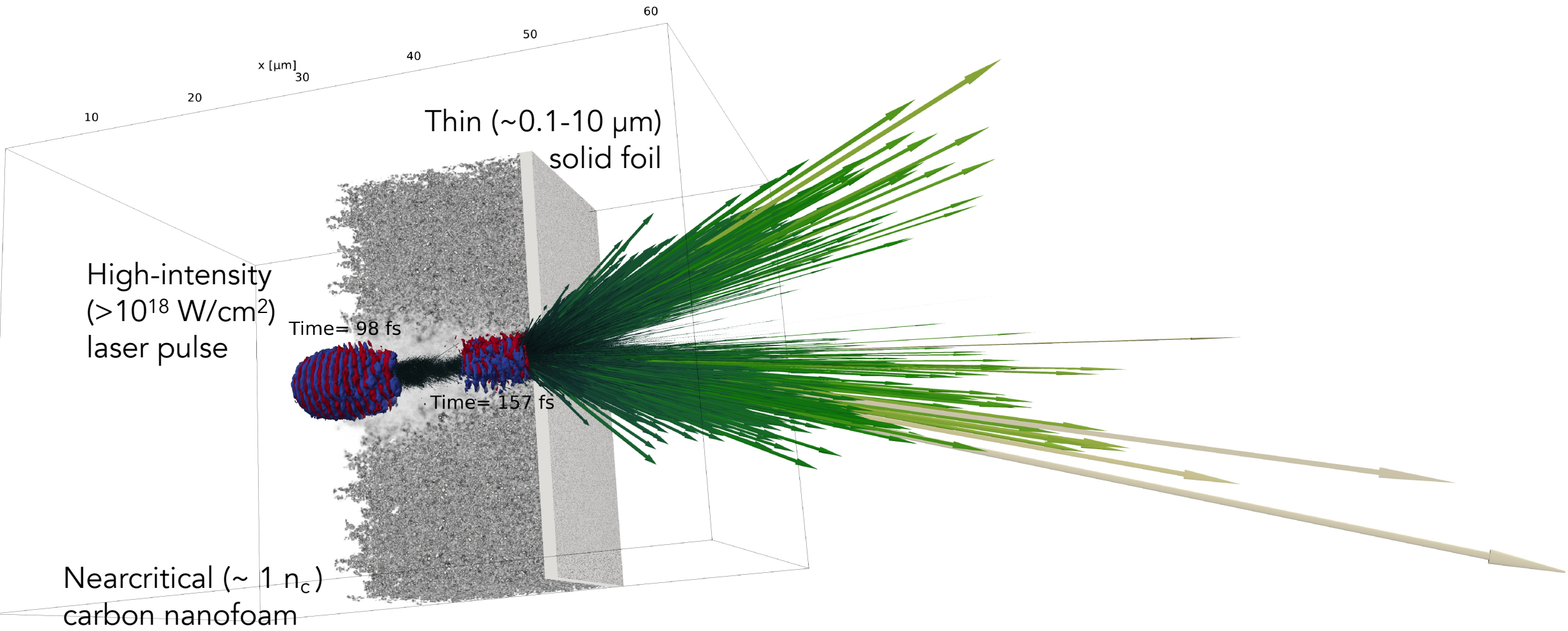
Laser-nanofoam interaction @ ps-scale



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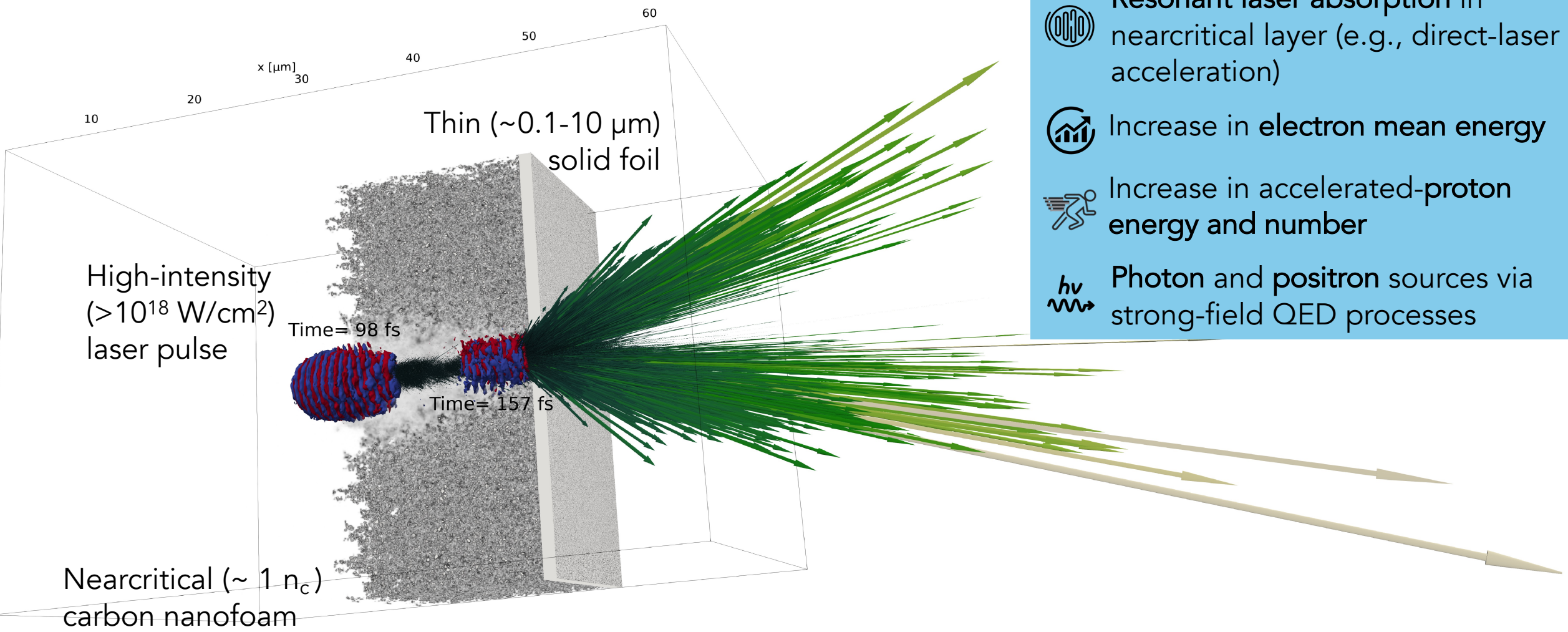

- **Resonant laser absorption** in nearcritical layer (e.g., direct-laser acceleration)
- Increase in **electron mean energy**
- Increase in accelerated-**proton energy and number**
- **Photon** and **positron** sources via strong-field QED processes

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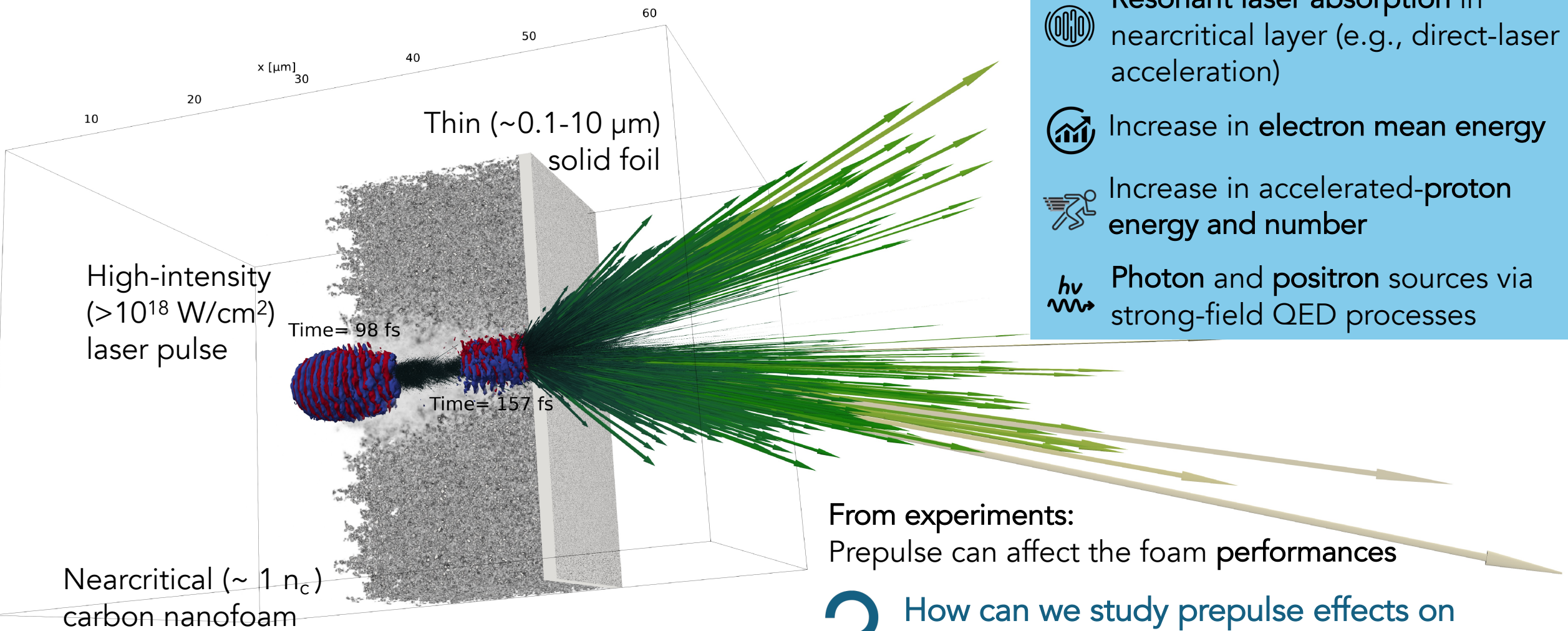

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From experiments:
Prepulse can affect the foam **performances**

? How can we study prepulse effects on nanofoams?

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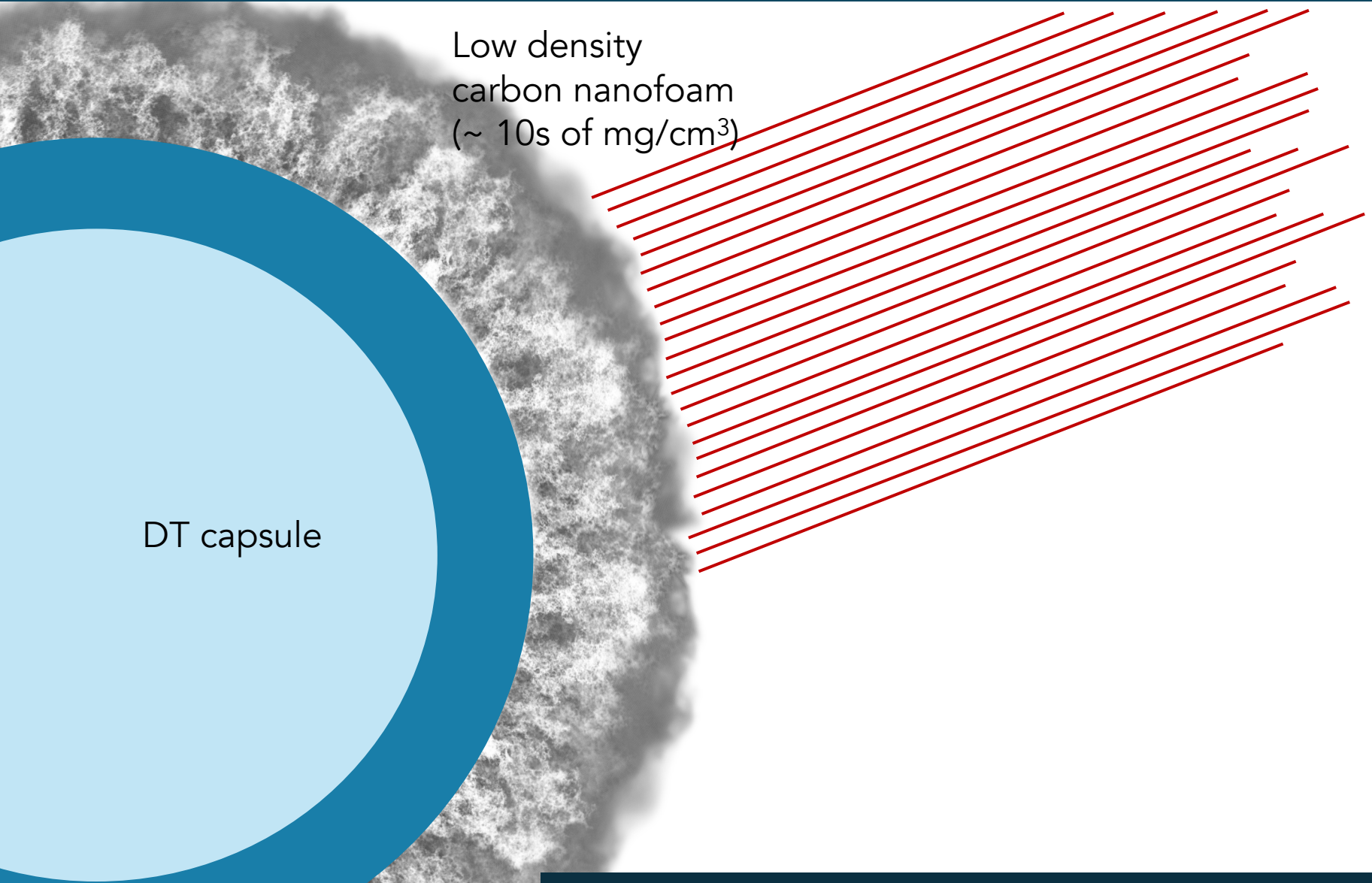
Laser-nanofoam interaction @ ns-scale



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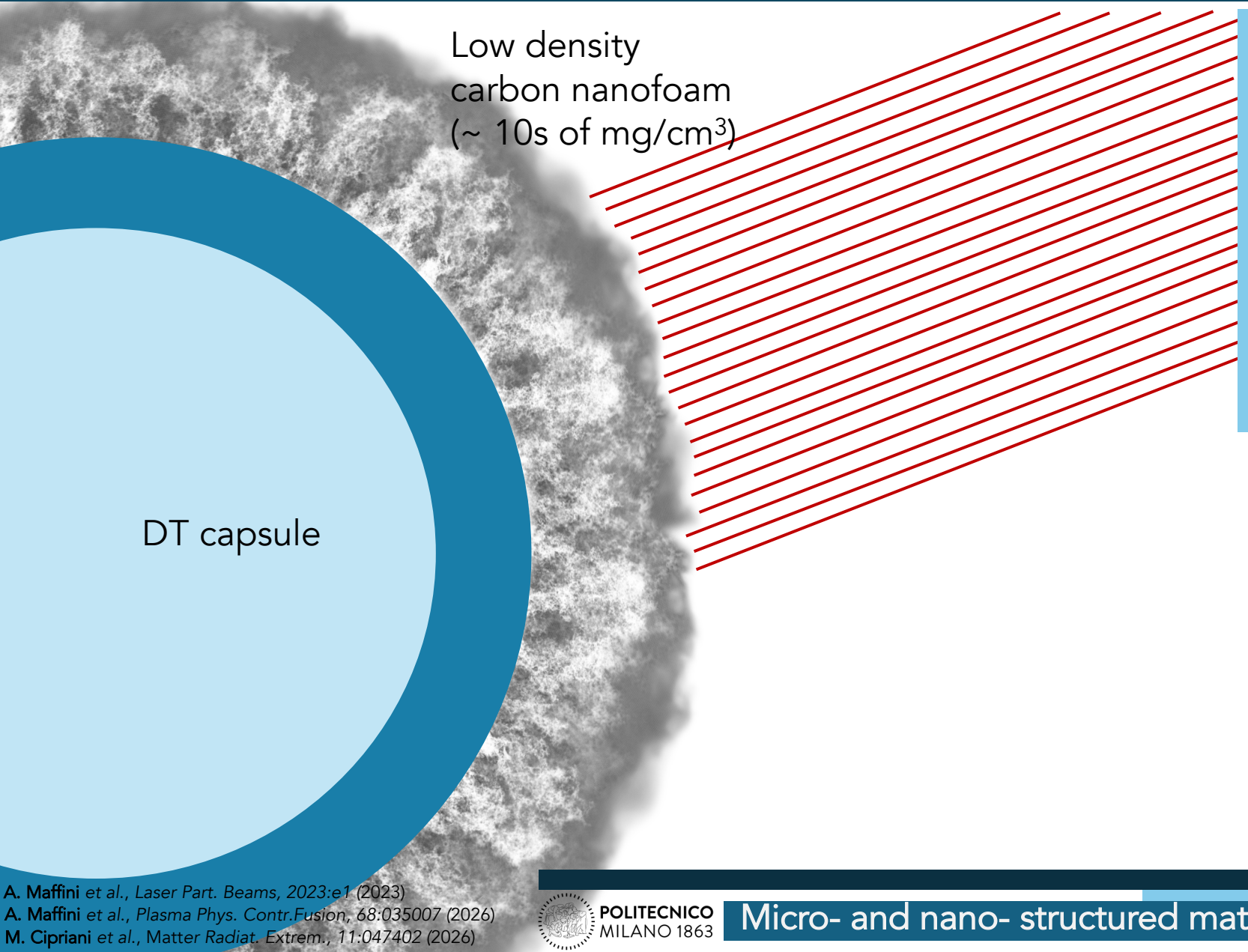

- Increase of the **ablation loading**
- **Mid-Z** material to reduce two-plasmon decay instability
- **Versatility** in tailoring density, morphology and thickness
- **Nanoscale fractal** morphology

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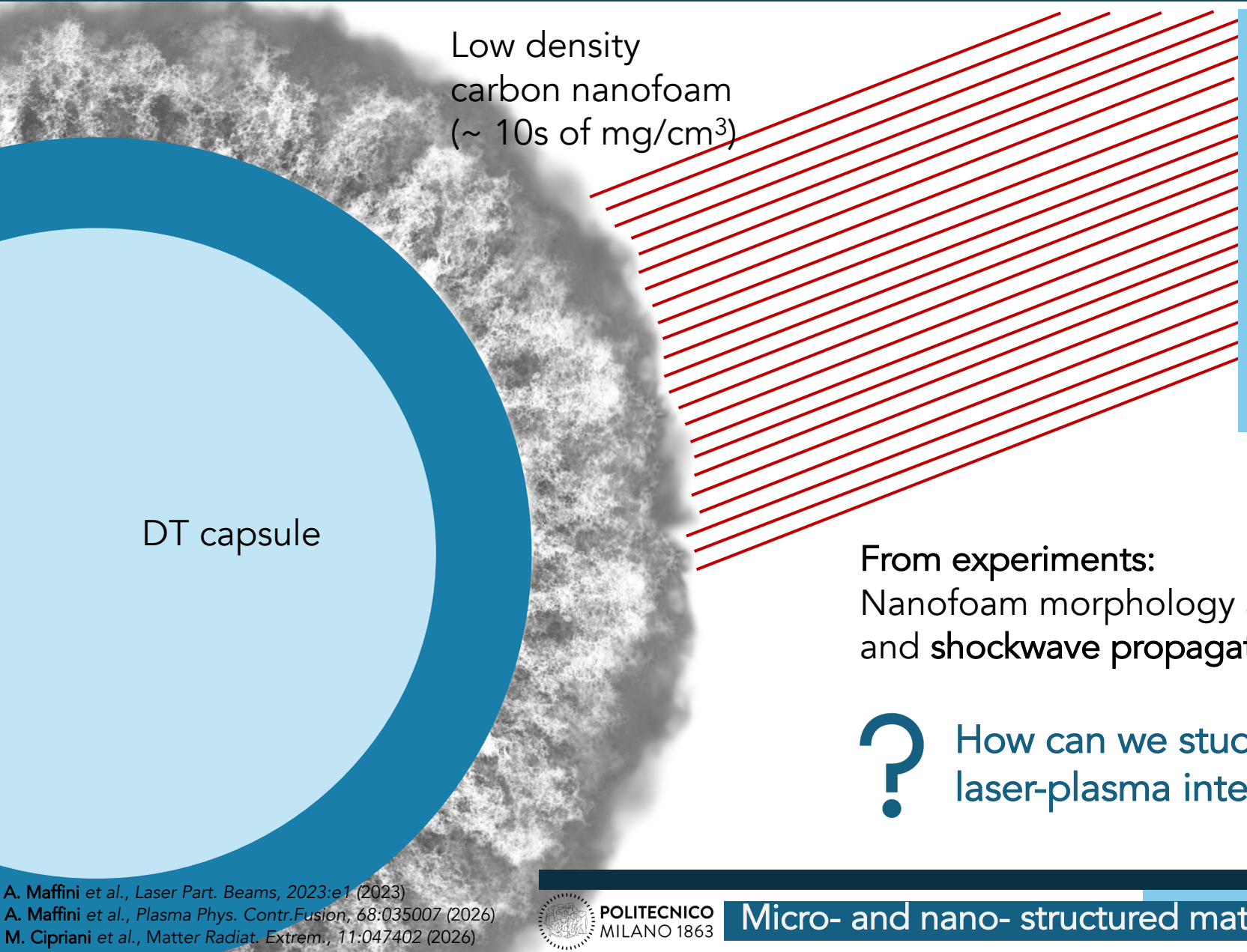

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From experiments:
Nanofoam morphology and density affect **ablation loading** and **shockwave propagation**

? How can we study the morphological effects on laser-plasma interaction?

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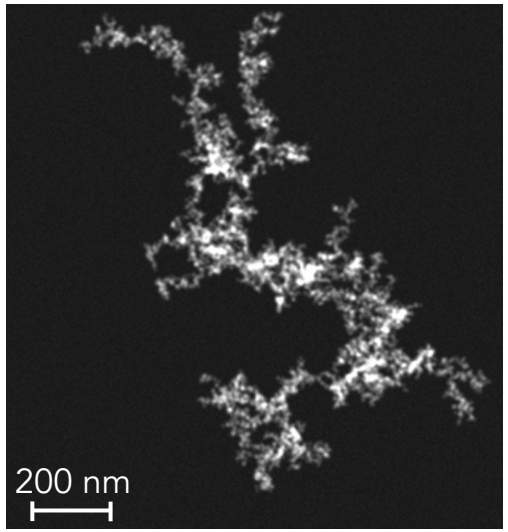
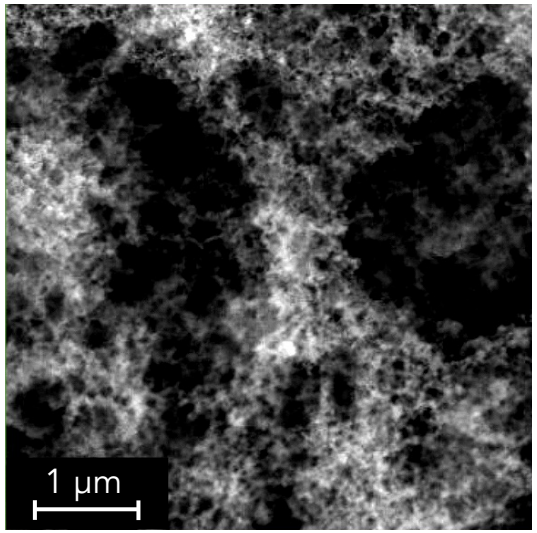
Studying laser-nanofoam interaction





~10s of nm ~1 µm **Spatial scale** ~10s of µm

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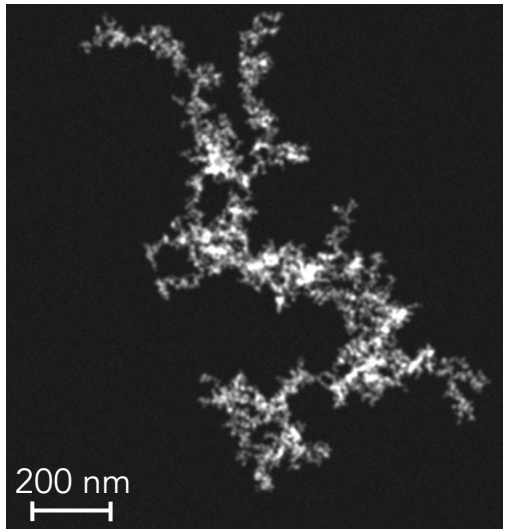

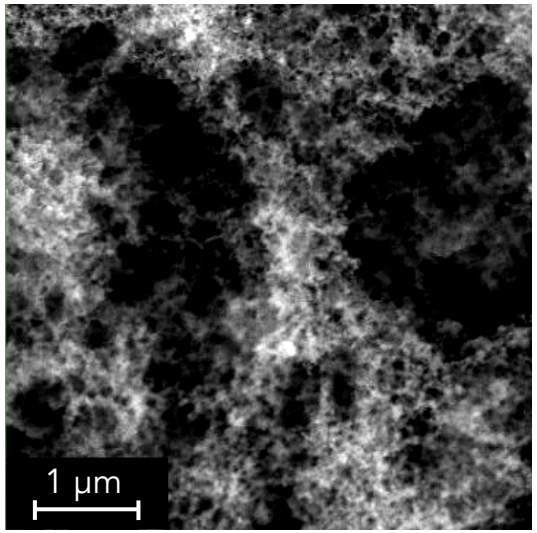

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Sub-wavelength components of foam (**nanoparticles, clusters**)

Affects laser **scattering** and **absorption**

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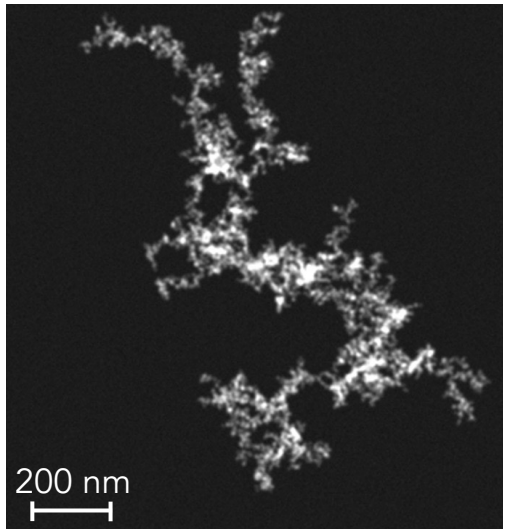

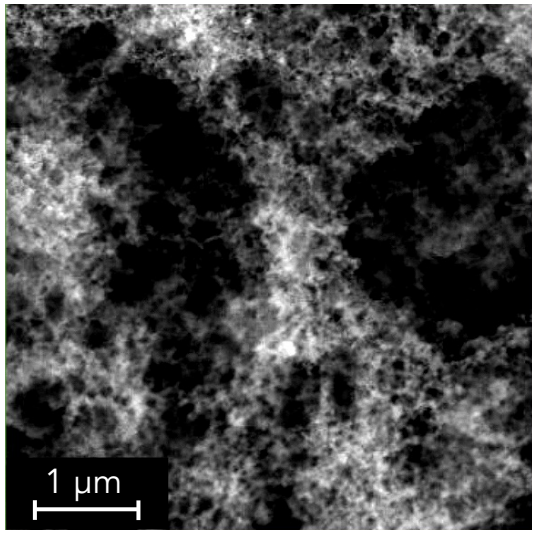

~10s of nm — ~1 µm — Spatial scale — ~10s of µm

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Affects laser **scattering** and **absorption**	Affects the **homogenisation** time

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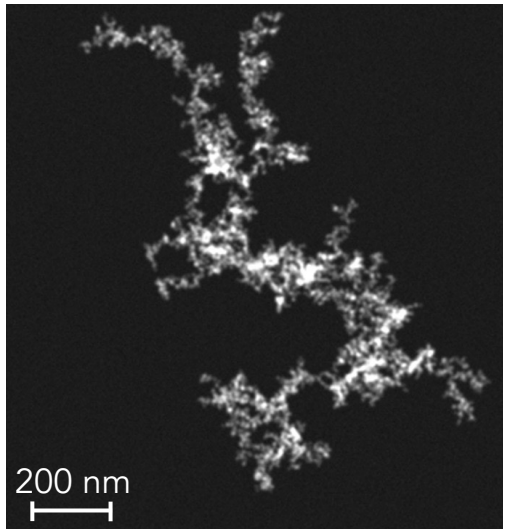

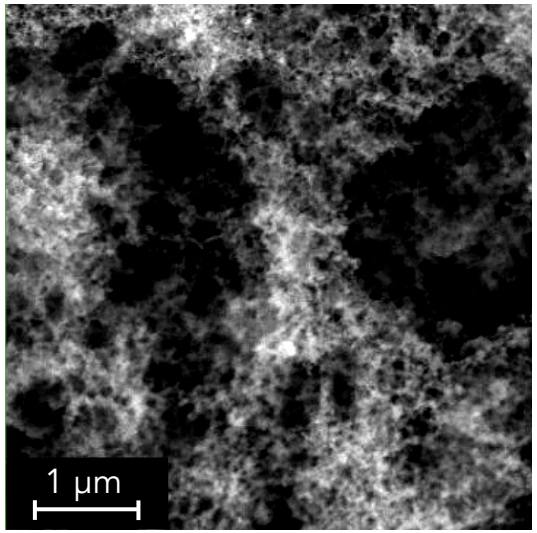

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Sub-wavelength components of foam (**nanoparticles, clusters**)	**Void fractions** of the nanofoam	Overall nanofoam **thickness**
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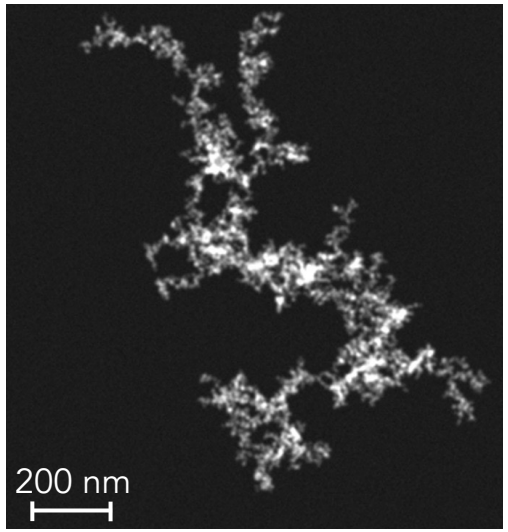

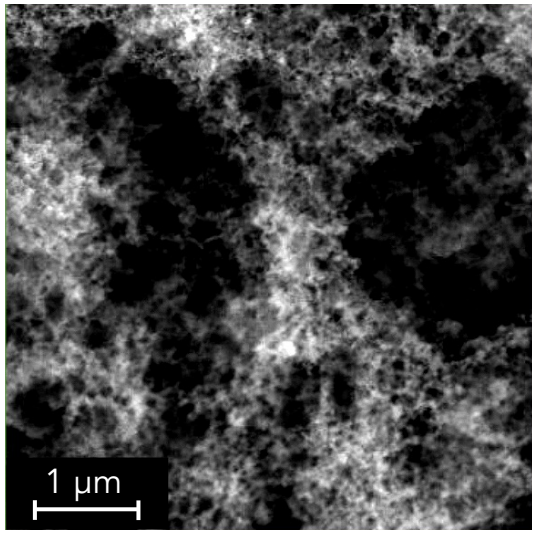

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Interplay among the spatial scales affects whole process

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Modelling of nanofoam homogenisation

Kinetic modelling

Fluid modelling

Modelling of nanofoam homogenisation

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Captures **non-equilibrium** and **non-collisional effects**

Self-consistent modelling of **laser scattering** with **sub-wavelength** structures

Limited **spatial** and **temporal** scales due to computational constraints

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Approximated ray optics modelling of **laser propagation**

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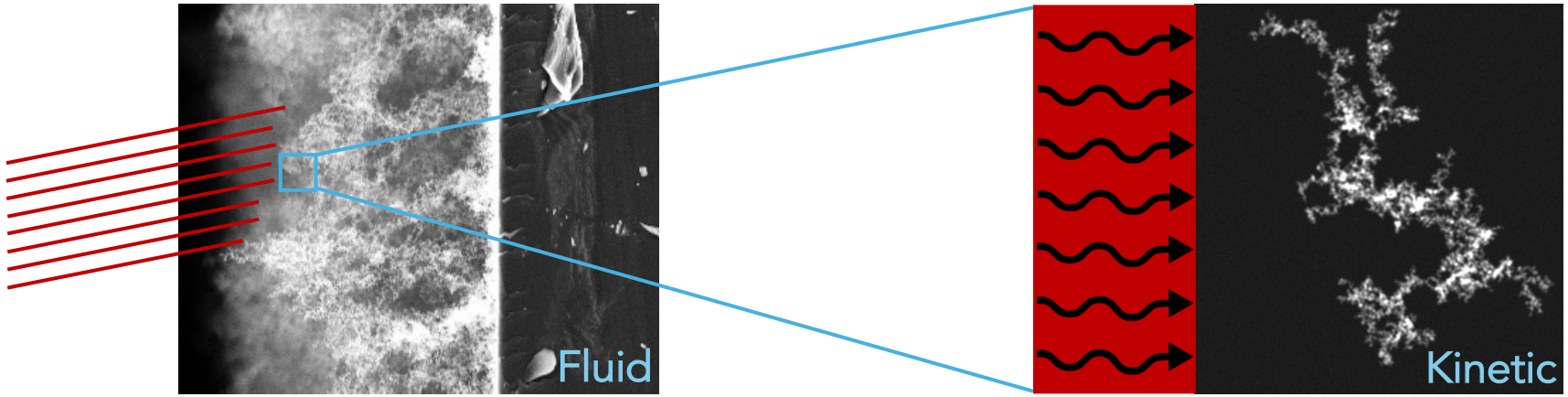

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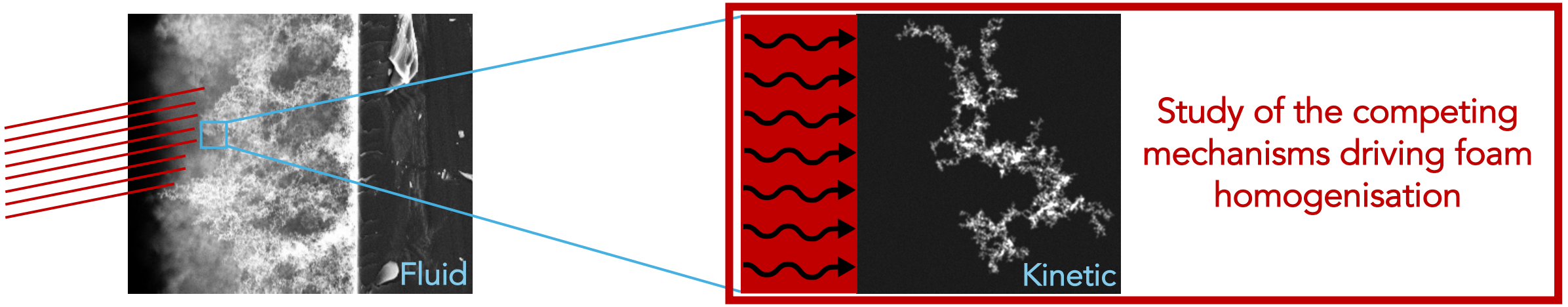


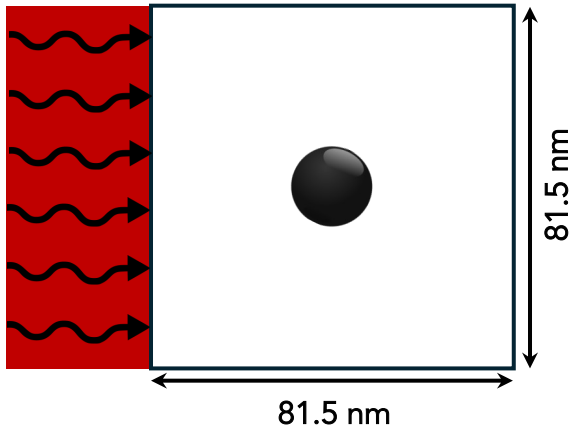
Study of the competing mechanisms driving foam homogenisation

Particle-in-cell simulations for nanofoam homogenisation

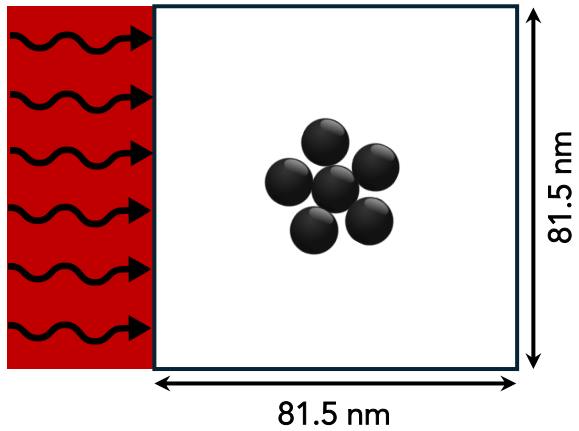
Smilei simulations of nanofoam **components** to study **kinetic effects** in foam **homogenisation**

2D

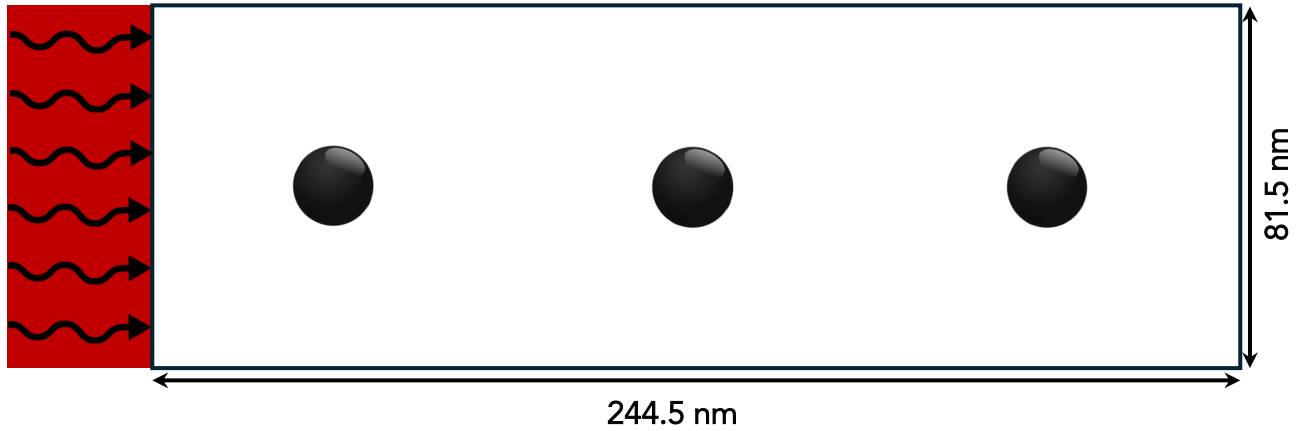
Intensity effects



Geometrical effects



Multiple nanoparticle effects



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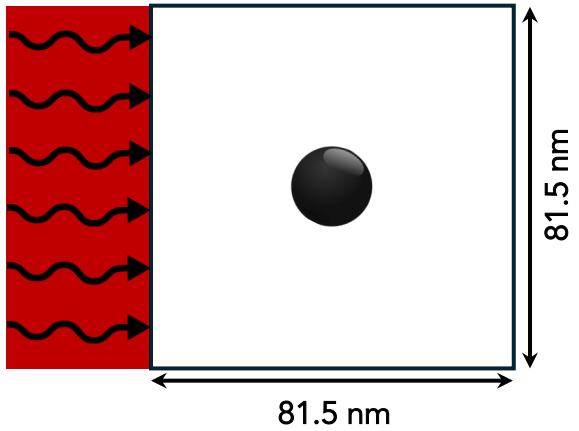
2D Intensity effects



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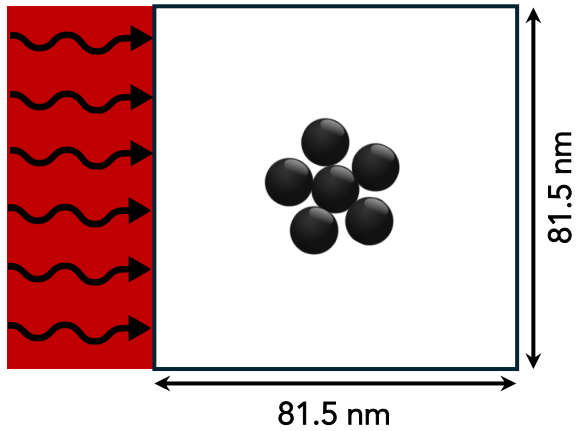
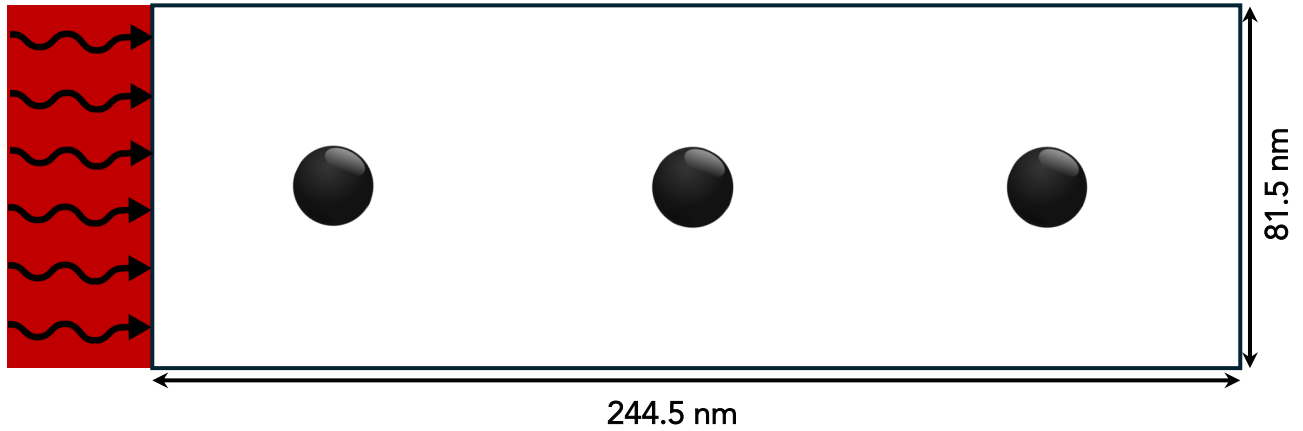
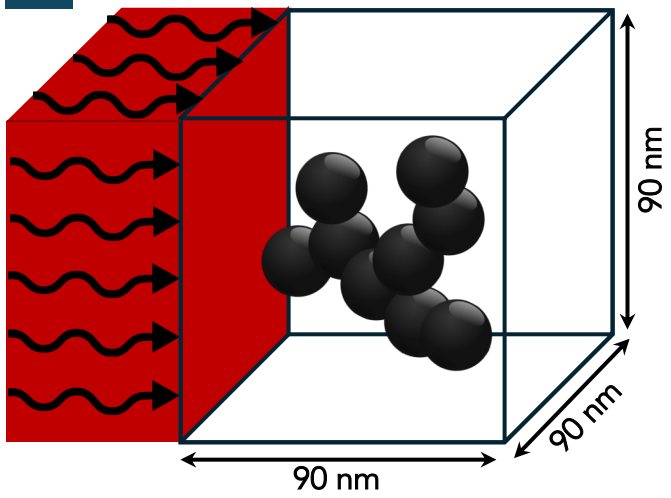


Multiple nanoparticle effects



3D Three-dimensional effects



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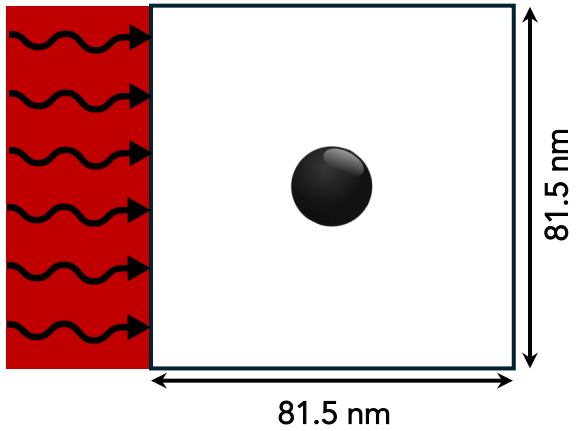
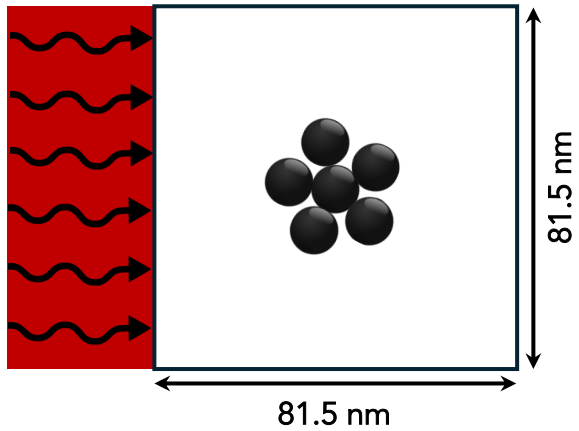
2D

Intensity effects



Geometrical effects



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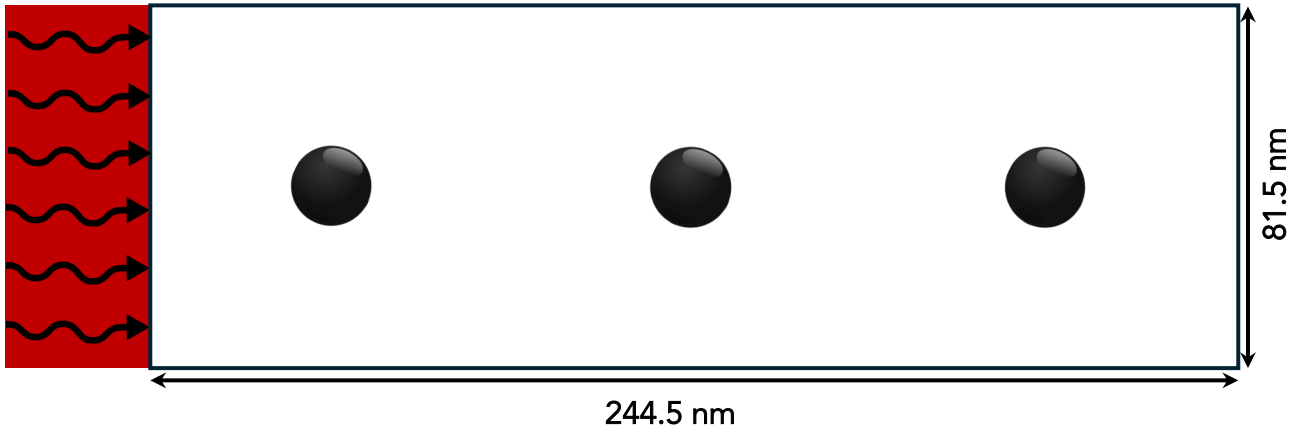

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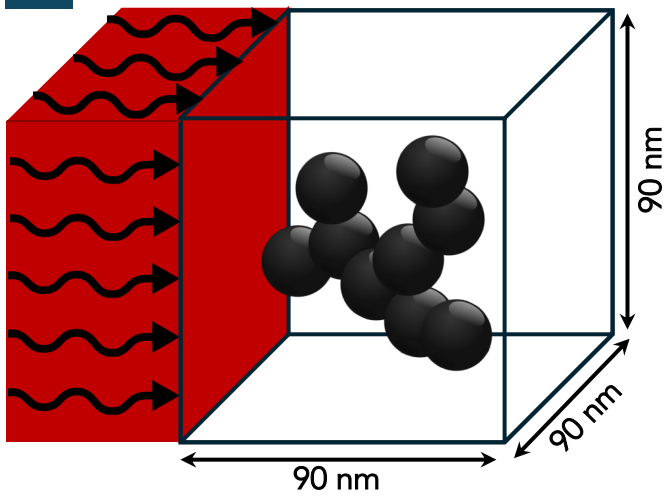


Laser irradiation until **homogenisation**

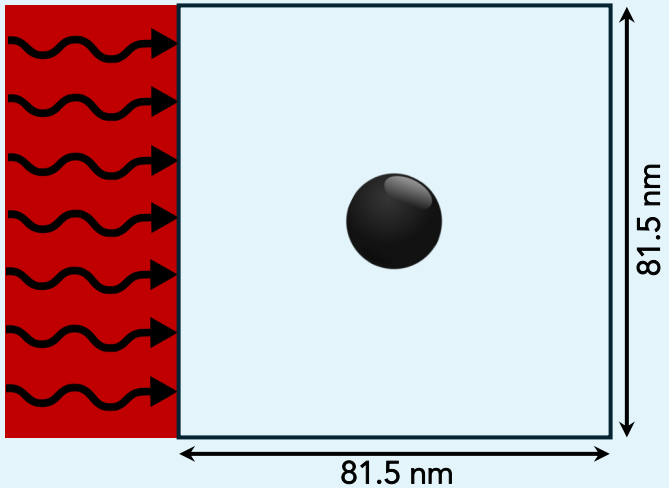
Periodic and **reflective** boundary conditions to simulate influence of macroscopic dimension

Box size adapted to reach nanofoam mean density @ homogenisation

Particle-in-cell simulations for nanofoam homogenisation

Smilei simulations of nanofoam **components** to study **kinetic effects** in foam **homogenisation**

2D



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- 10^{12}-10^{20}-W/cm^2 **intensity**
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- **Periodic** boundary conditions

Simulation parameters

Δx = 0.04 nm
c.f.l. = 0.90
Electrons per cell:
383
Ions per cell:
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3D

Particle-in-cell simulations for nanofoam homogenisation

Smilei simulations of nanofoam **components** to study **kinetic effects** in foam **homogenisation**

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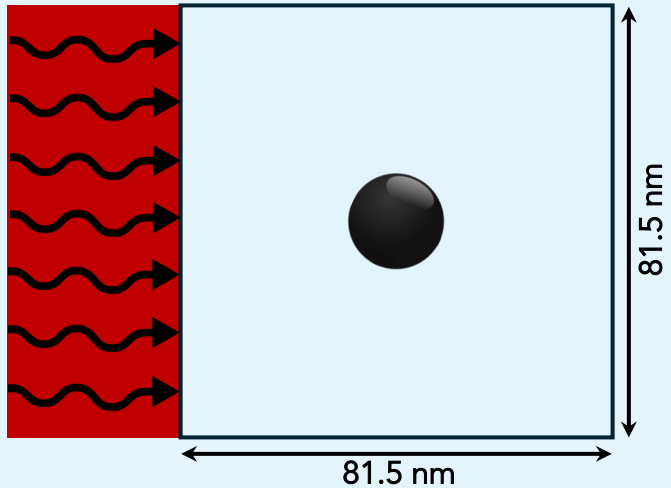

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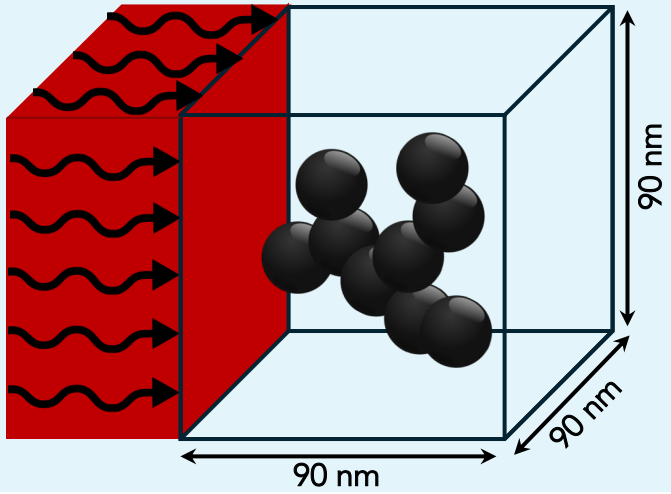

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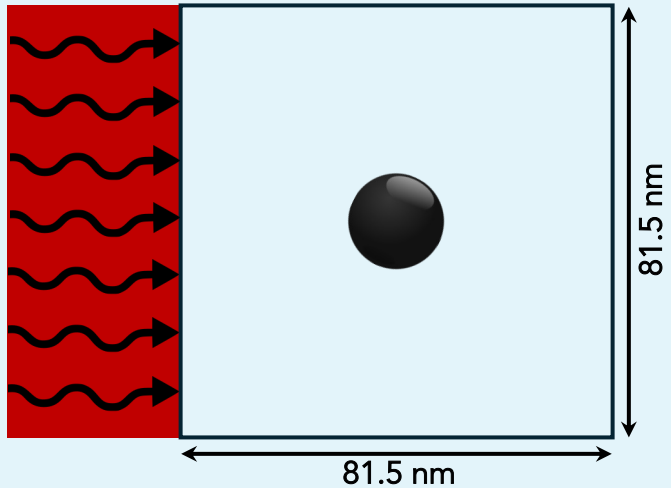

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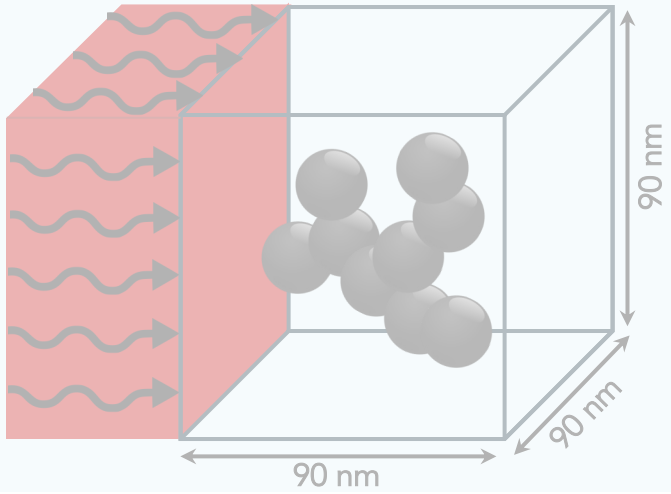

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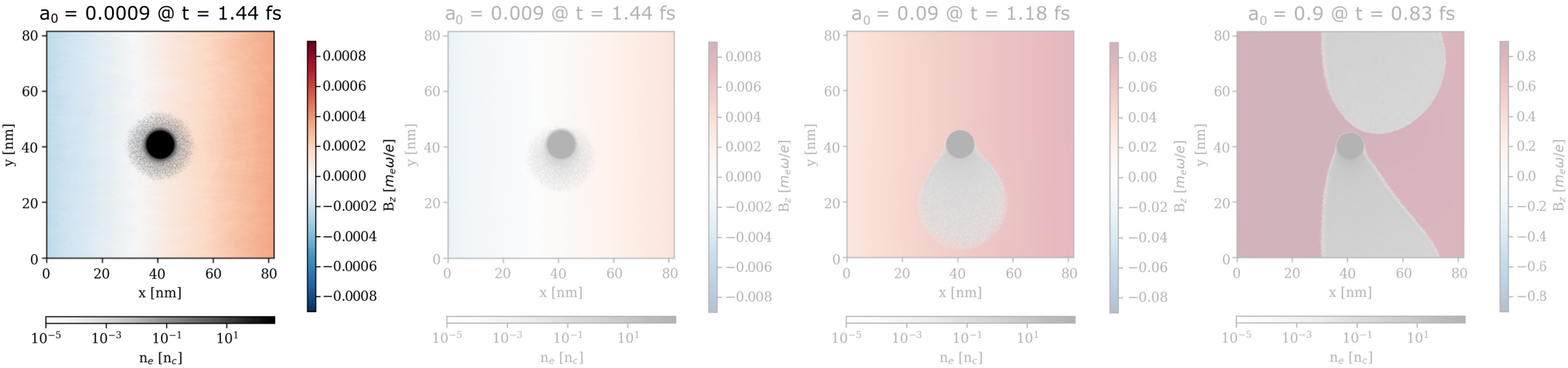
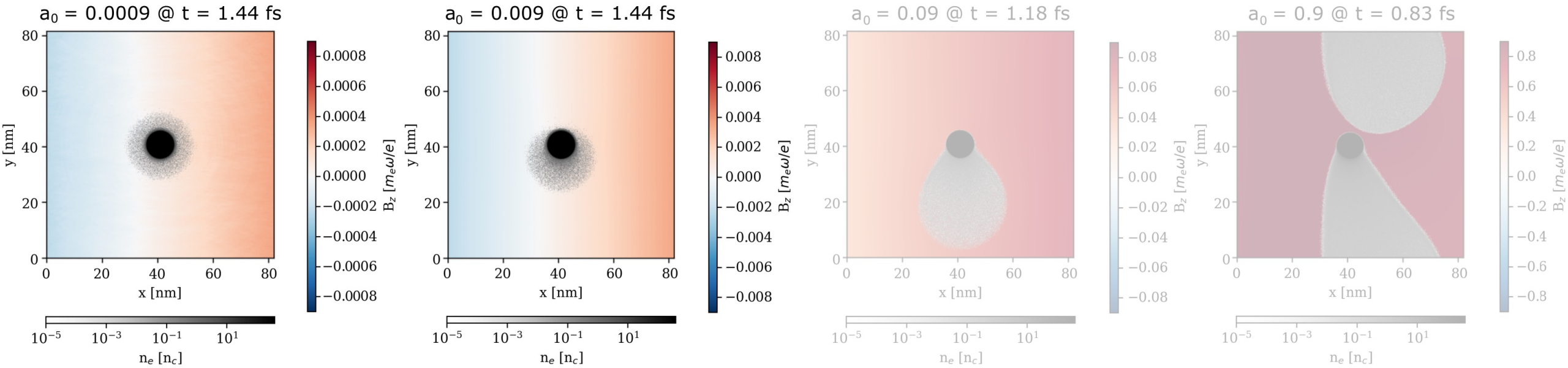
Laser intensity effects on homogenisation



10^{12} 10^{14} Intensity [W/cm^2] 10^{16} 10^{18}

Laser interacting via **collisions**

Laser intensity effects on homogenisation



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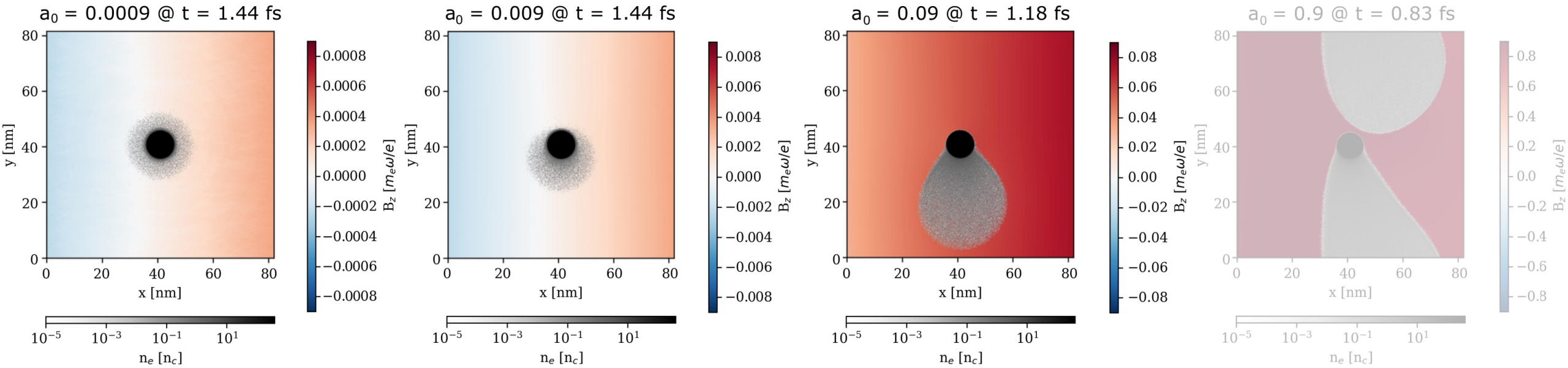
Laser interacting via **collisions**

Electrons **ejected** by laser field

Laser intensity effects on homogenisation



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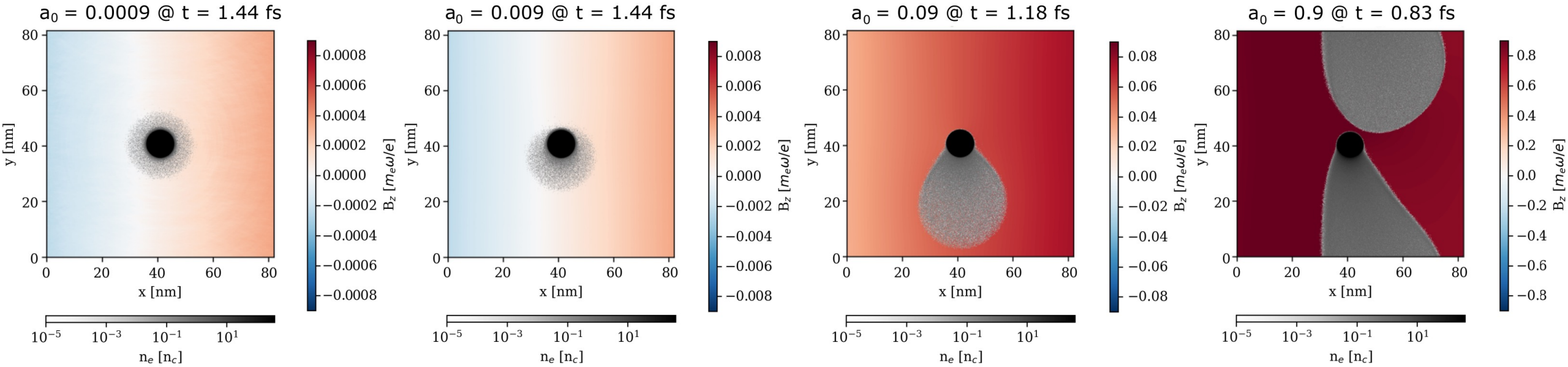
Non-collisional ablation increases

Laser intensity effects on homogenisation



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Relativistic electron motion (8-shape)

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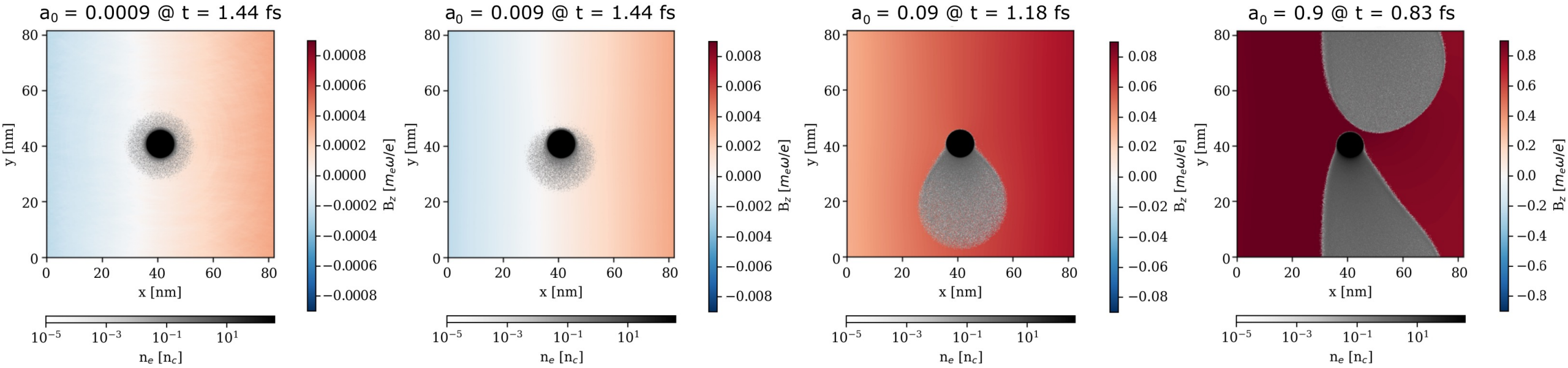

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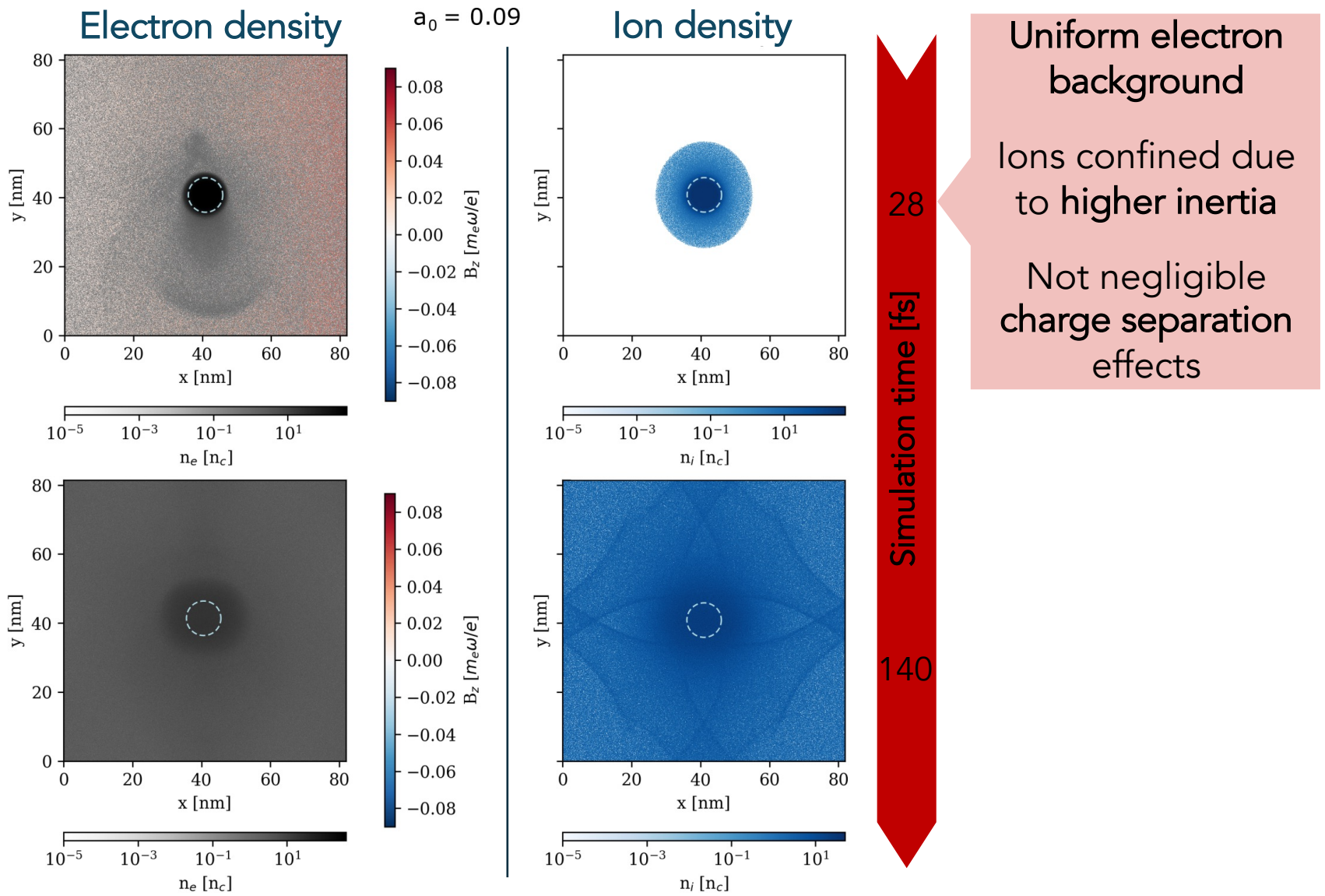
Laser interacting via **collisions**	Electrons **ejected** by laser field	**Non-collisional** ablation increases	**Relativistic** electron motion (8-shape)

Homogenisation and laser absorption strongly affected by **non-collisional processes** at modest intensity

Which processes affect most homogenisation?

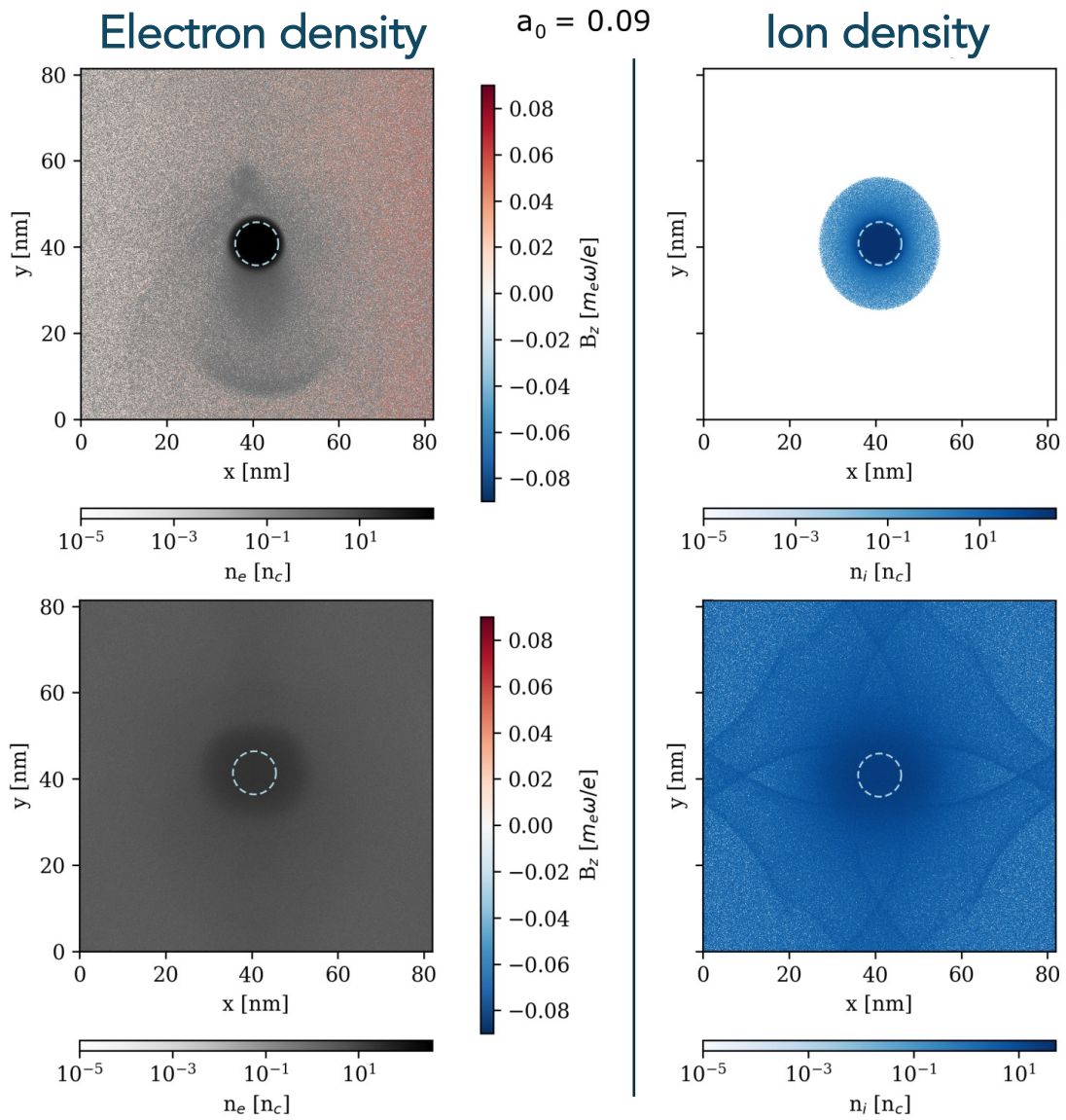


Uniform electron background

Ions confined due to **higher inertia**

Not negligible **charge separation** effects

Which processes affect most homogenisation?



Simulation time [fs]

28

Uniform electron background

Ions confined due to **higher inertia**

Not negligible **charge separation** effects

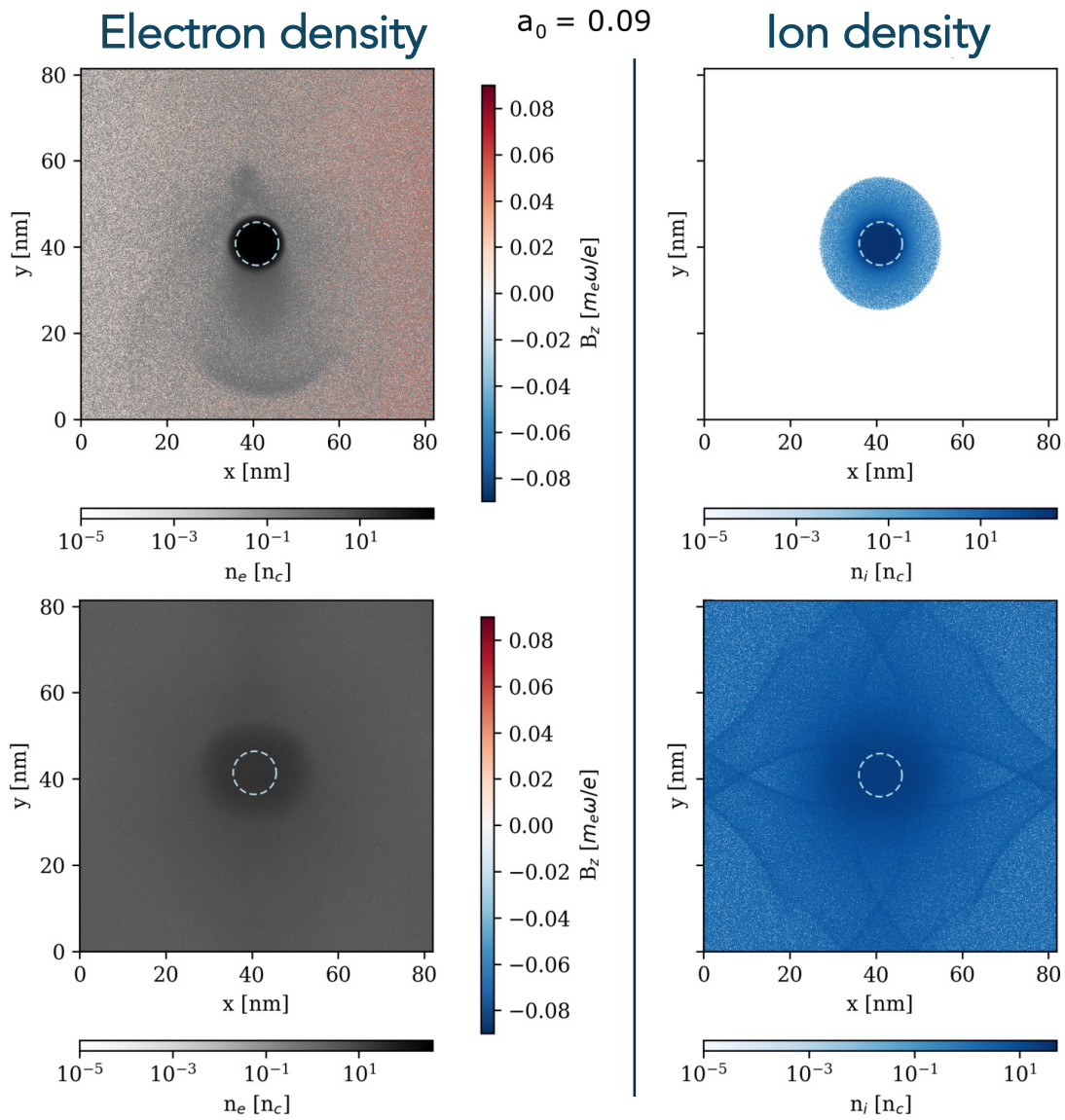
140

Increase in the dense plasma diameter

Homogenisation of the **background**

Total homogenisation in ~180 fs

Which processes affect most homogenisation?



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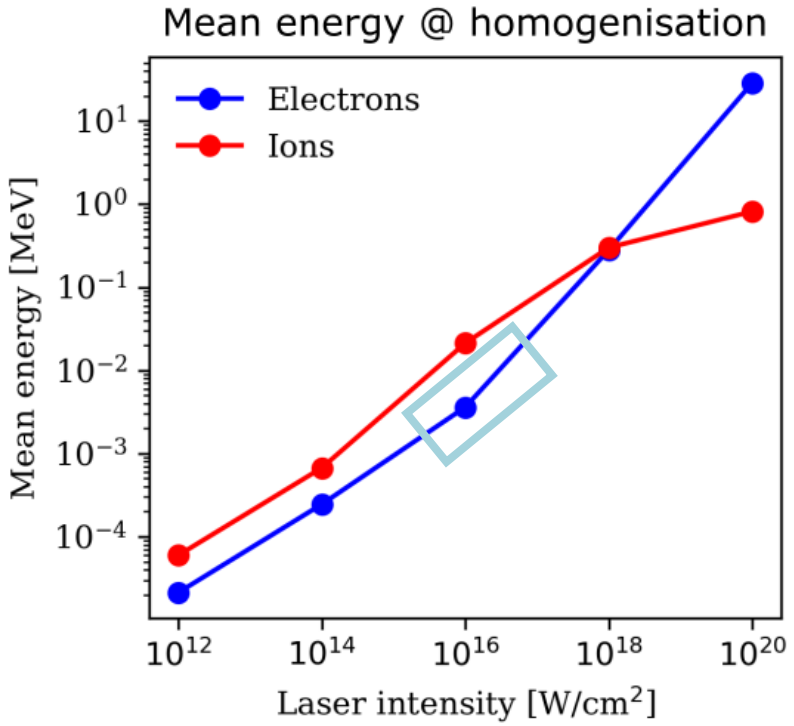

Slope change indicating additional **electron heating (v×B)**

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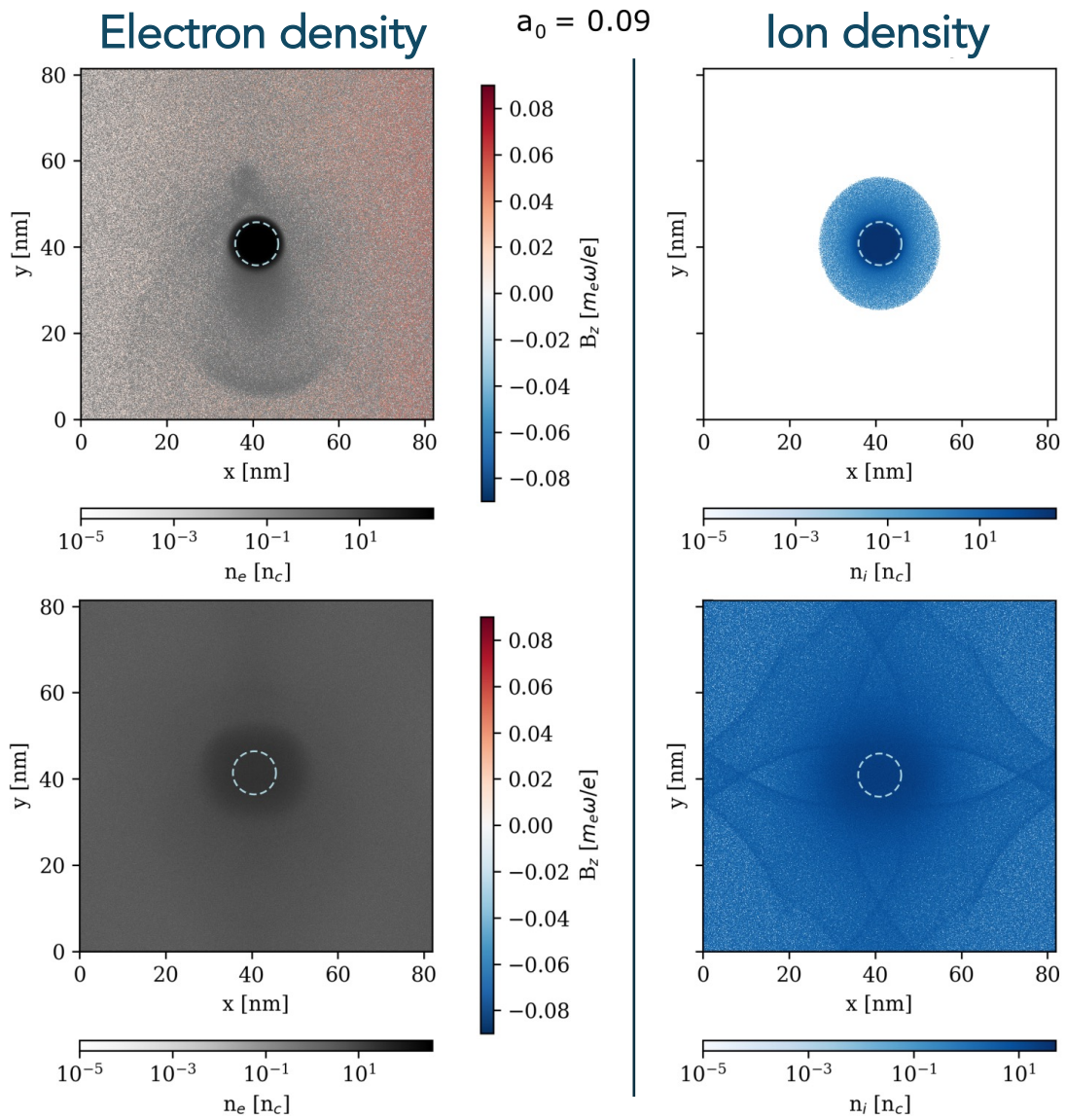

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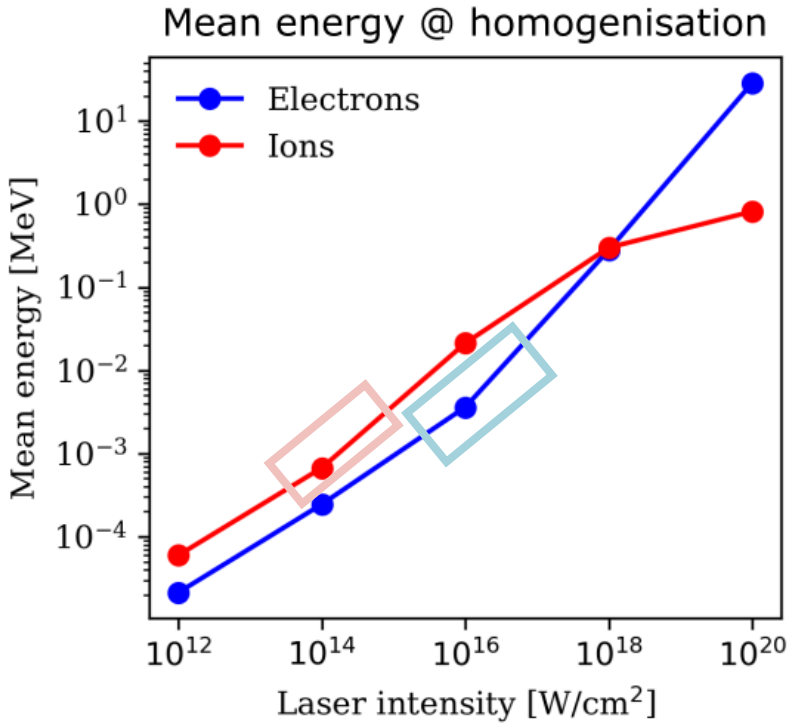

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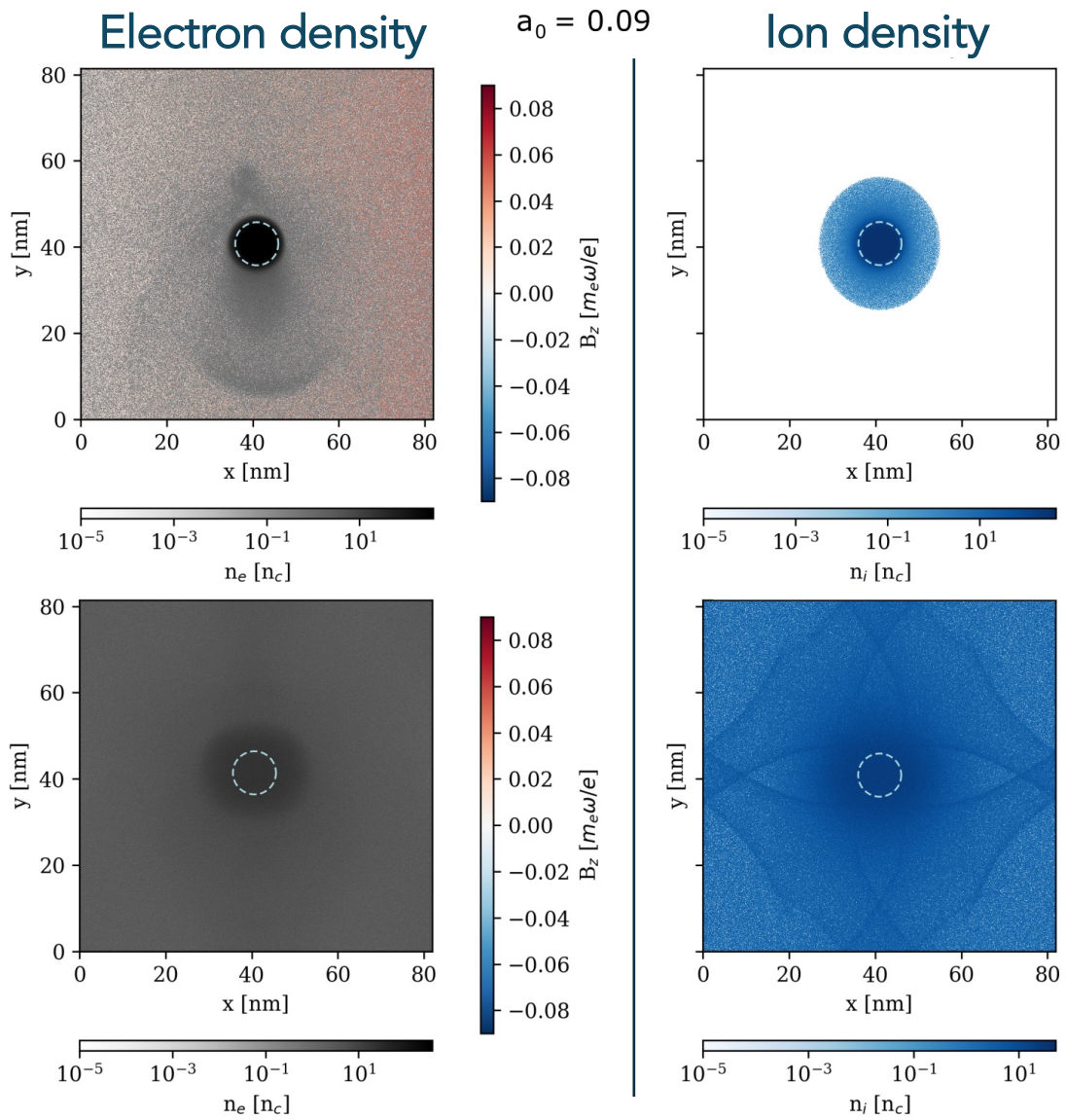

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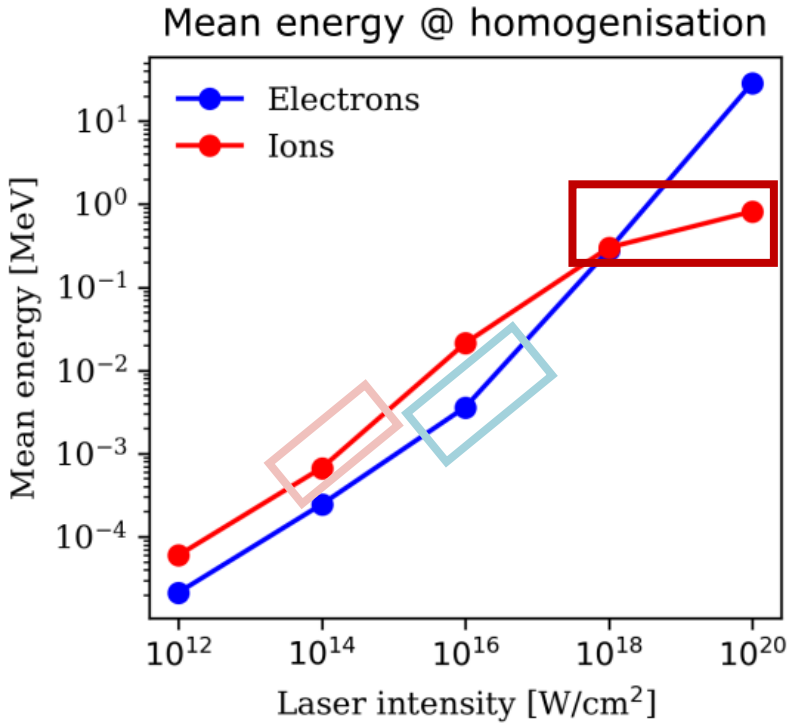


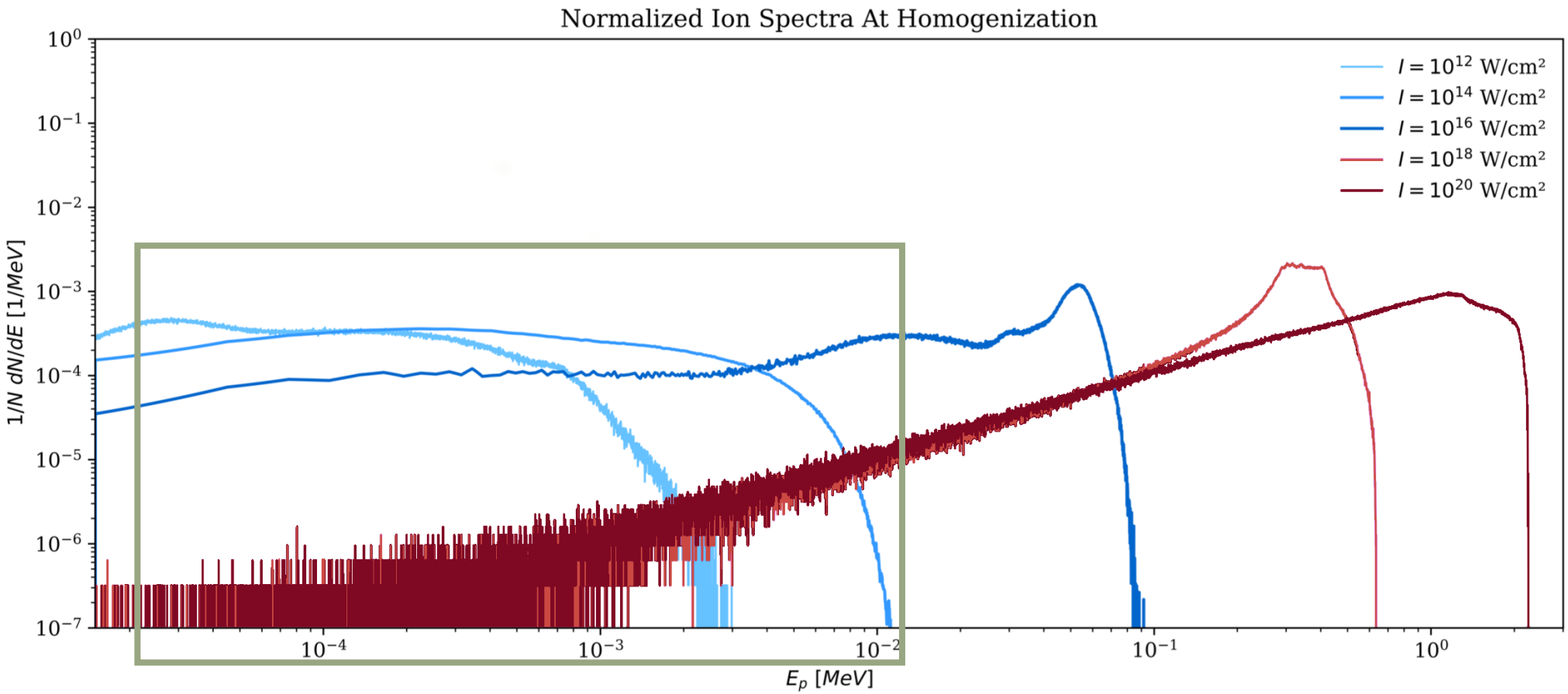
Slope change indicating additional **electron heating (v×B)**

Slope change indicating additional **ion heating**

Saturation of ion heating indicating **Coulomb explosion**

Which processes affect most homogenisation?

Quasi **Maxwellian** ion energy spectra up to
$I=10^{14}$ W/cm^2



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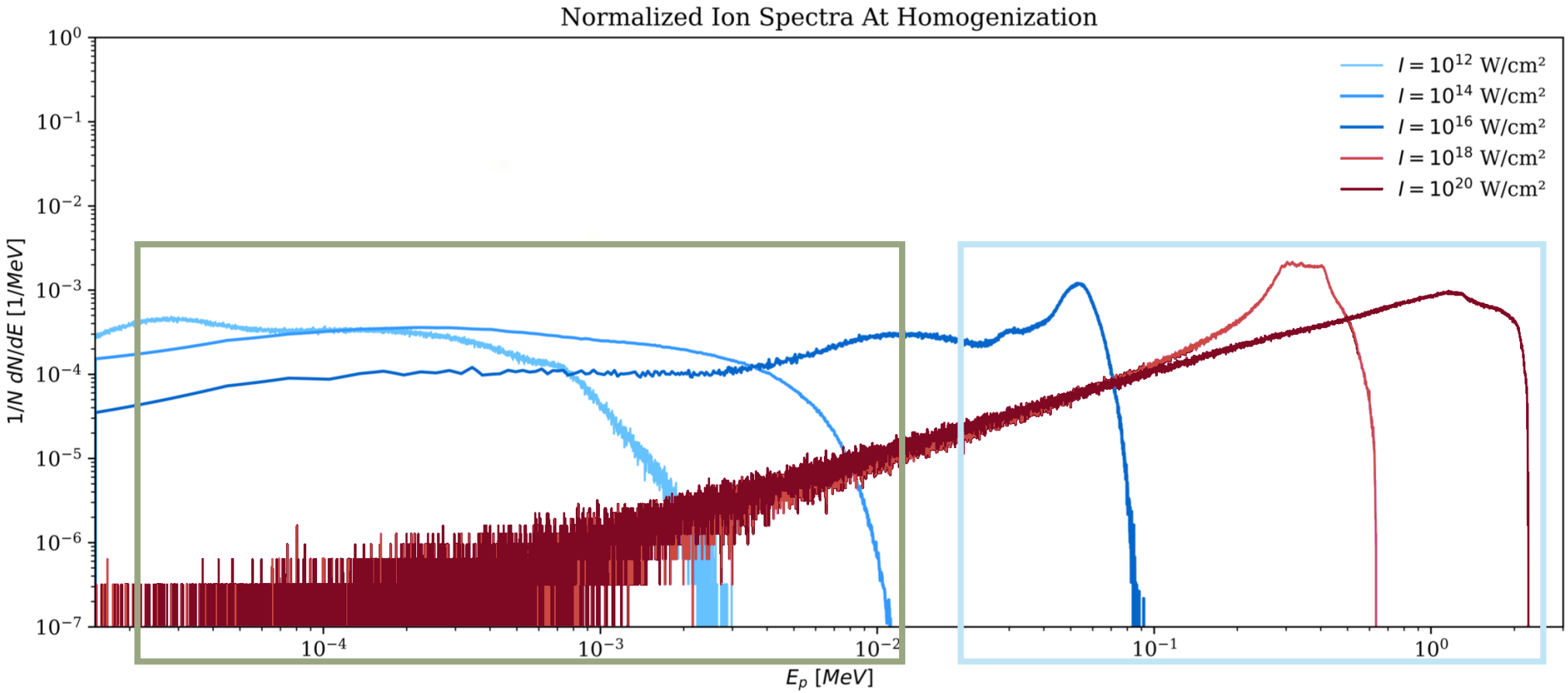
Quasi **Maxwellian** ion energy spectra up to $I=10^{14}$ W/cm^2

High-energy peaks below $I=10^{16}$ W/cm^2 ascribable to **charge separation** (Coulomb explosion)



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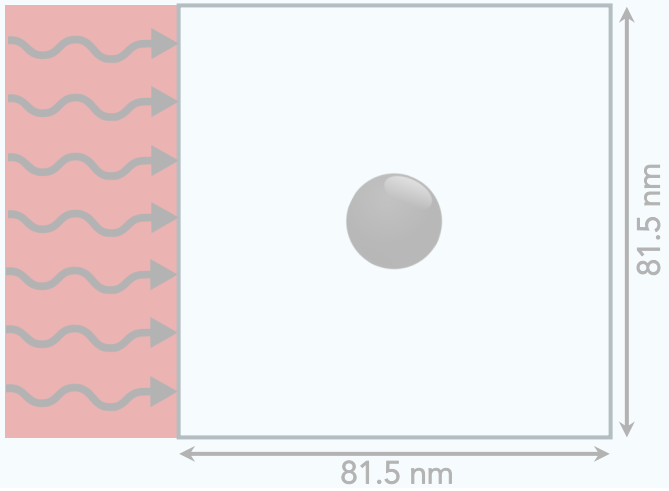

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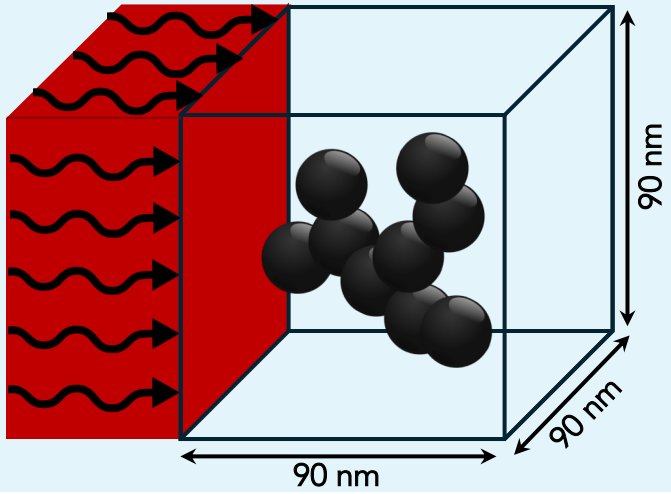

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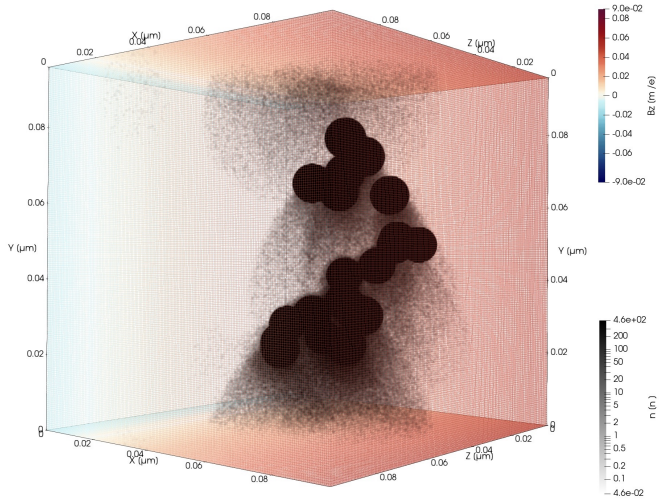
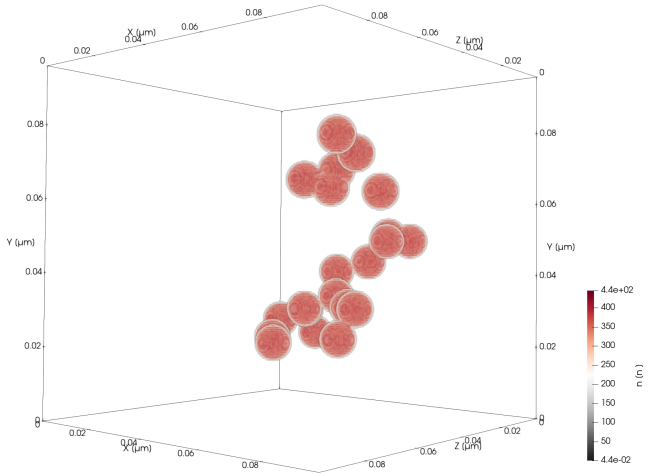
Homogenisation of a realistic nanofoam cluster

t = 1.4 fs

Electrons



Ions



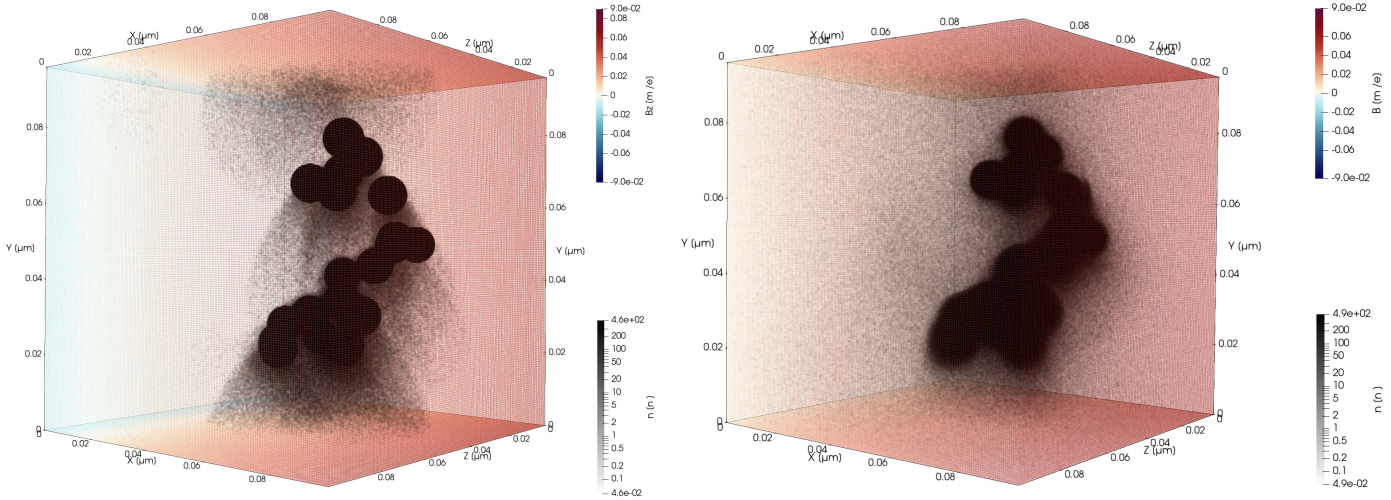
Electrons pushed out

Homogenisation of a realistic nanofoam cluster

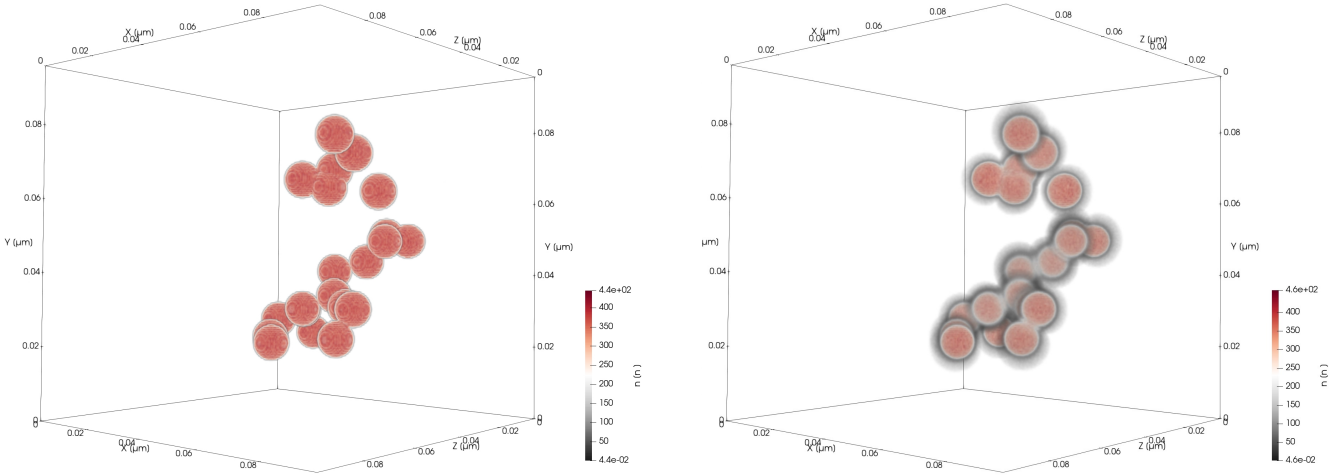
t = 1.4 fs

t = 12 fs

Electrons



Ions



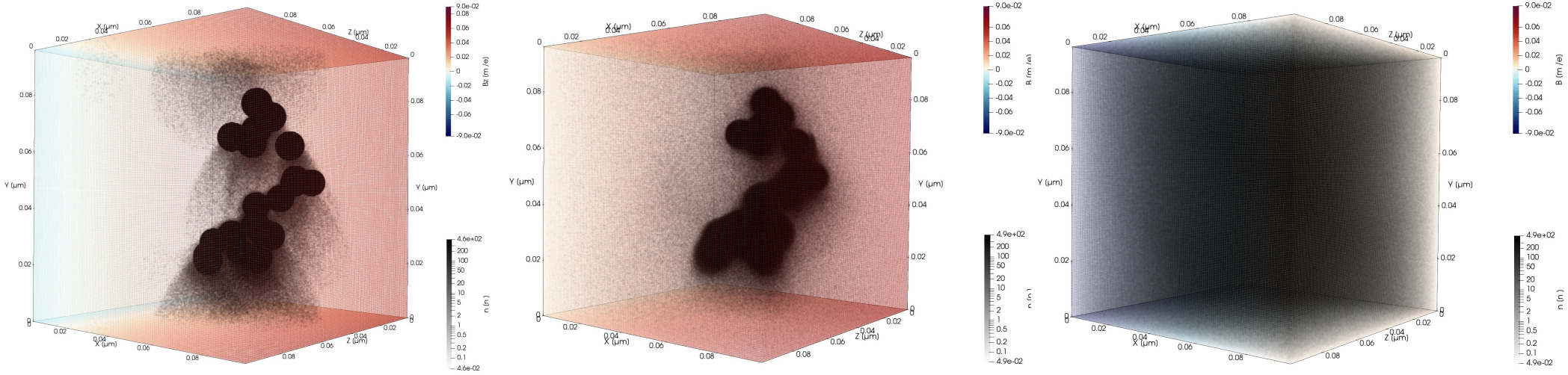
Electrons pushed out

Ions expand by charge separation

Homogenisation of a realistic nanofoam cluster

t = 1.4 fs | t = 12 fs | t = 102 fs

Electrons



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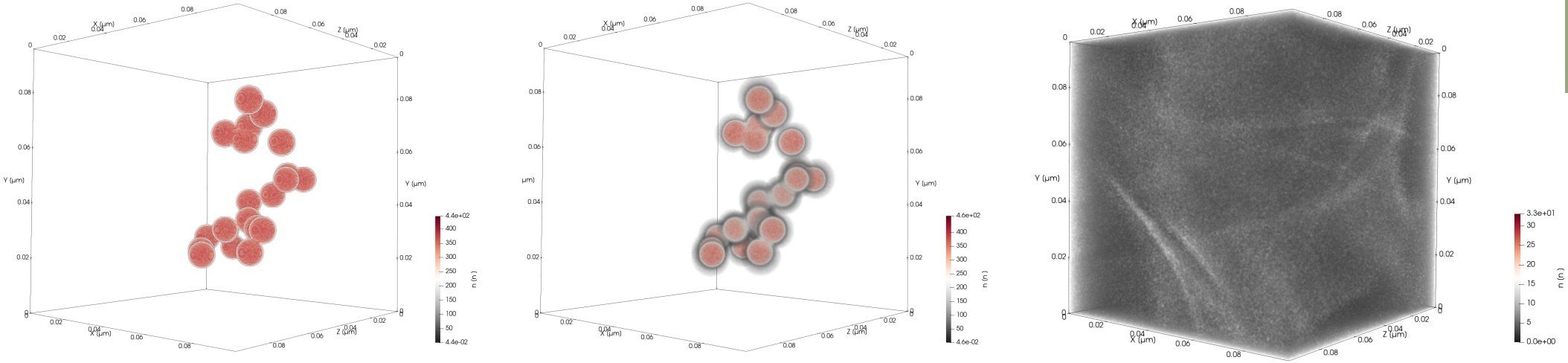


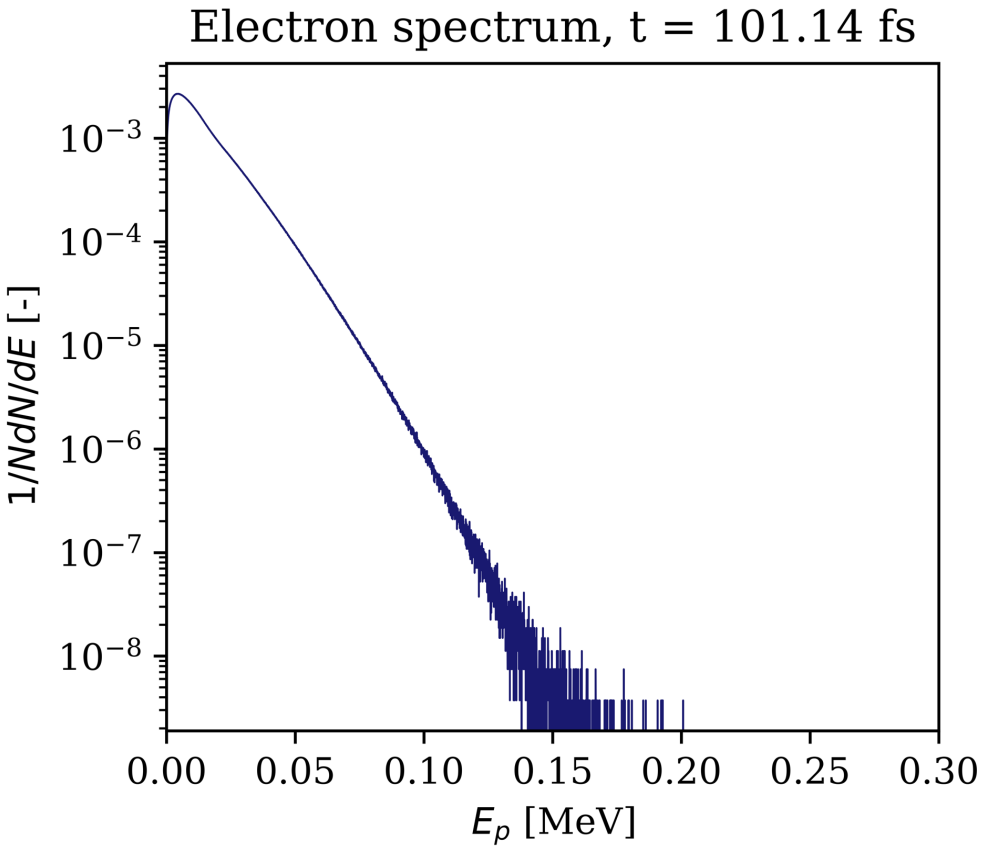
Decrease in homogenisation time with respect to 2D!

Electrons pushed out

Ions expand by charge separation

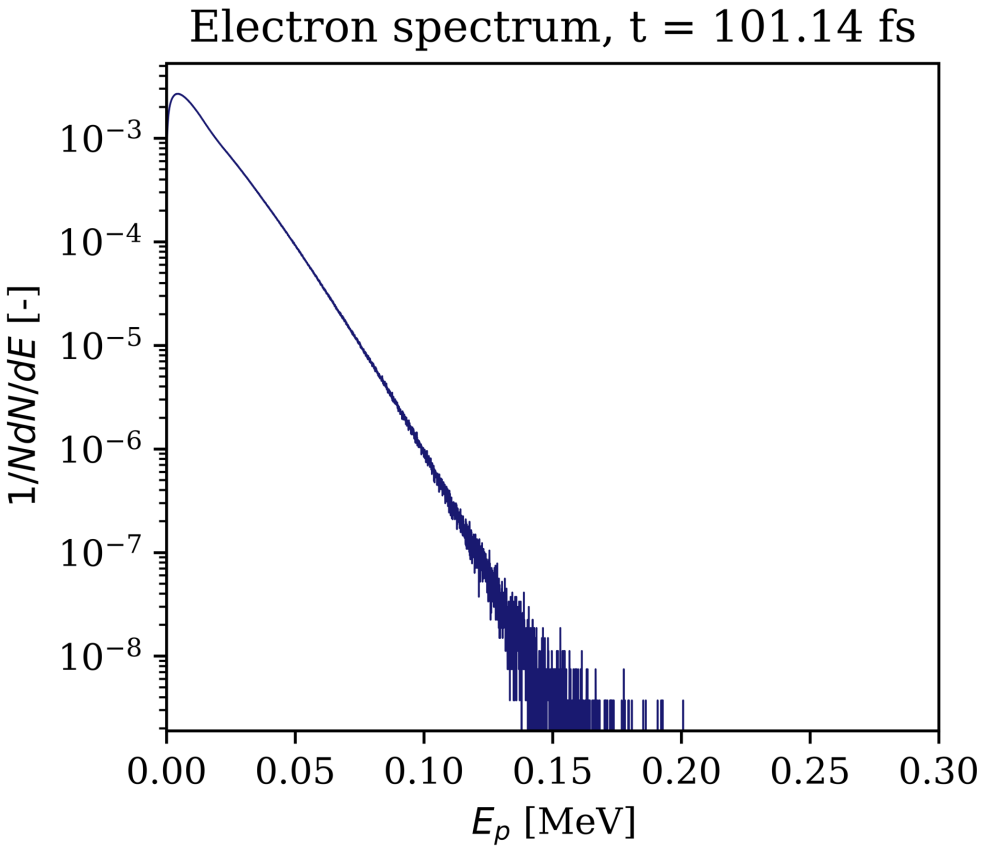
Cluster **homogenised**

Homogenisation of a realistic nanofoam cluster



Maxwellian electron energy spectrum

Homogenisation of a realistic nanofoam cluster



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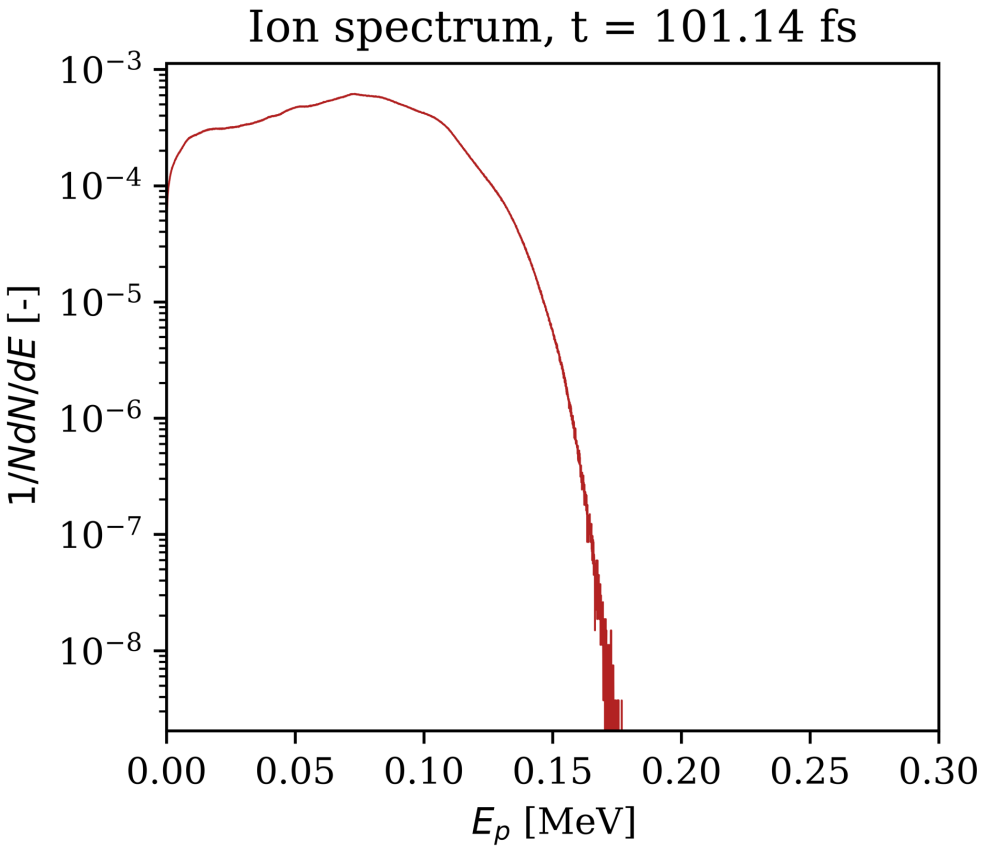
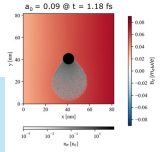
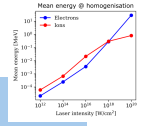


Non-Maxwellian ion energy spectrum peaked at high energy (charge separation)

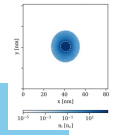
Conclusions and future developments



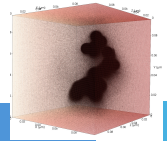
Assessed main laser **absorption** mechanisms



Assessed effects of **laser intensity** on foam **sub-wavelength** homogenisation

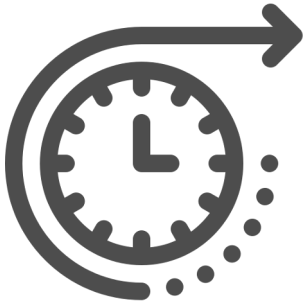


Observed **charge separation** effects in foam homogenisation



Observed **geometrical effects** in **homogenisation** process in 3D simulation

Assessed the key homogenisation mechanisms in **ICF/prepulse-relevant scenarios**



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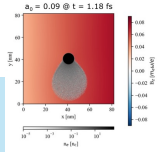

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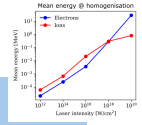
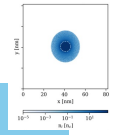
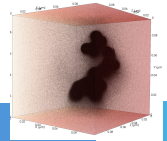


Assessed effects of **laser intensity** on foam **sub-wavelength** homogenisation



Observed **charge separation** effects in foam homogenisation



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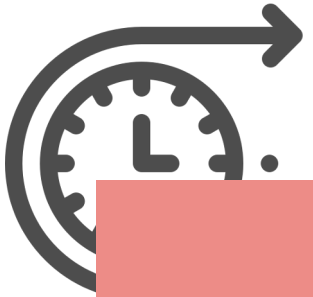

Study of intensity effects in 3D

Study of effects of **laser scattering** in homogenisation in 3D

Analytical modelling of cluster homogenisation under laser irradiation

Coupling of **kinetic** result to **fluid** simulations to simulate **prepulse effects** on nanofoams

Coupling of **kinetic** result to **fluid** simulations of nanofoam as **ablators for ICF**

Acknowledgments

- Our research line group @ NanoLab


M. Passoni


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A. Maffini

Post-docs


F. Mirani


D. Orecchia


D. Vavassori

PhD students


K. Ambrogioni


M. S. Galli De Magistris


M. Iaccarino

Master students


L. Filippi


M. Andreoni


F. Piziali

- The ENEA research group (*Fabrizio Consoli, Mattia Cipriani*)
- The collaboration with LLNL research group (*Marta Galbiati*)
- Simulations were performed on the Galileo100 machine hosted at CINECA
- The computing resources and the related technical support used for this work have been provided also by CRESCO-ENEAGRID High Performance Computing infrastructure and its staff

Thank you for your attention!

kevin.ambrogioni@polimi.it

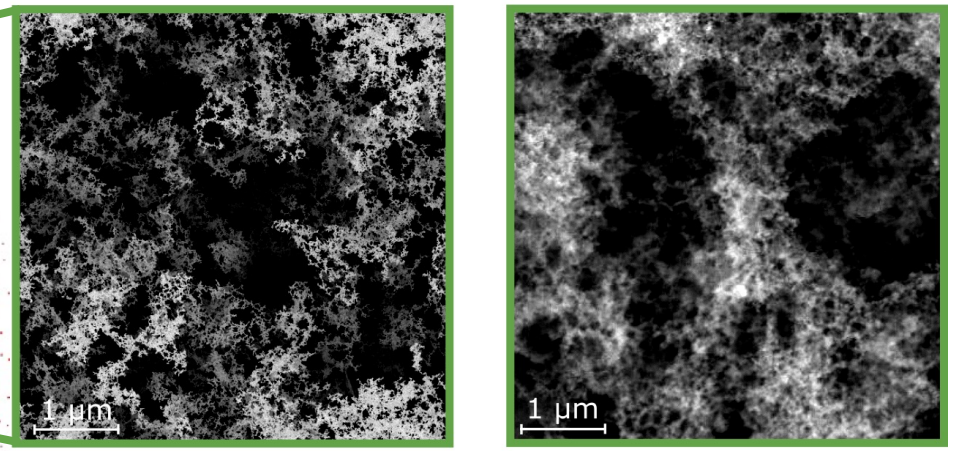
www.ensure.polimi.it

How do we produce carbon nanofoams?

Thin (~0.1-10 μm) solid foil

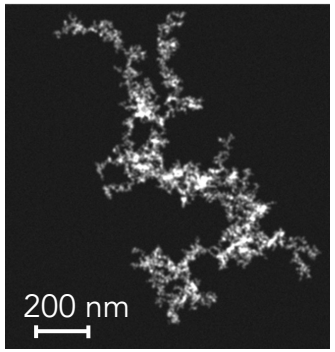
High-intensity (>10^{18} W/cm^2) laser pulse

Nearcritical (~ 1 n_c) carbon nanofoam



~8-mg/cm^3 foam density

Carbon nanofoams deposited with pulsed-laser deposition @ NanoLab

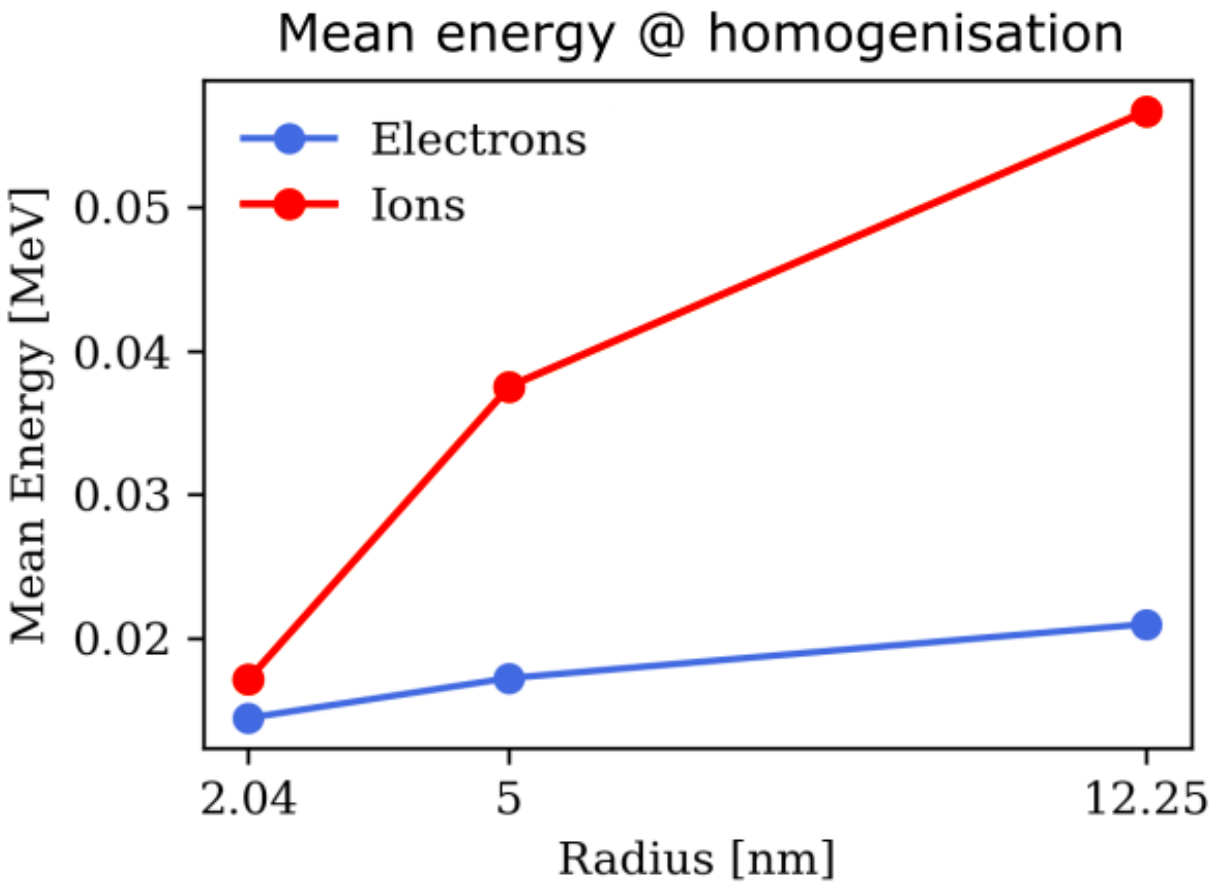


Clusters of nm-carbon-particles

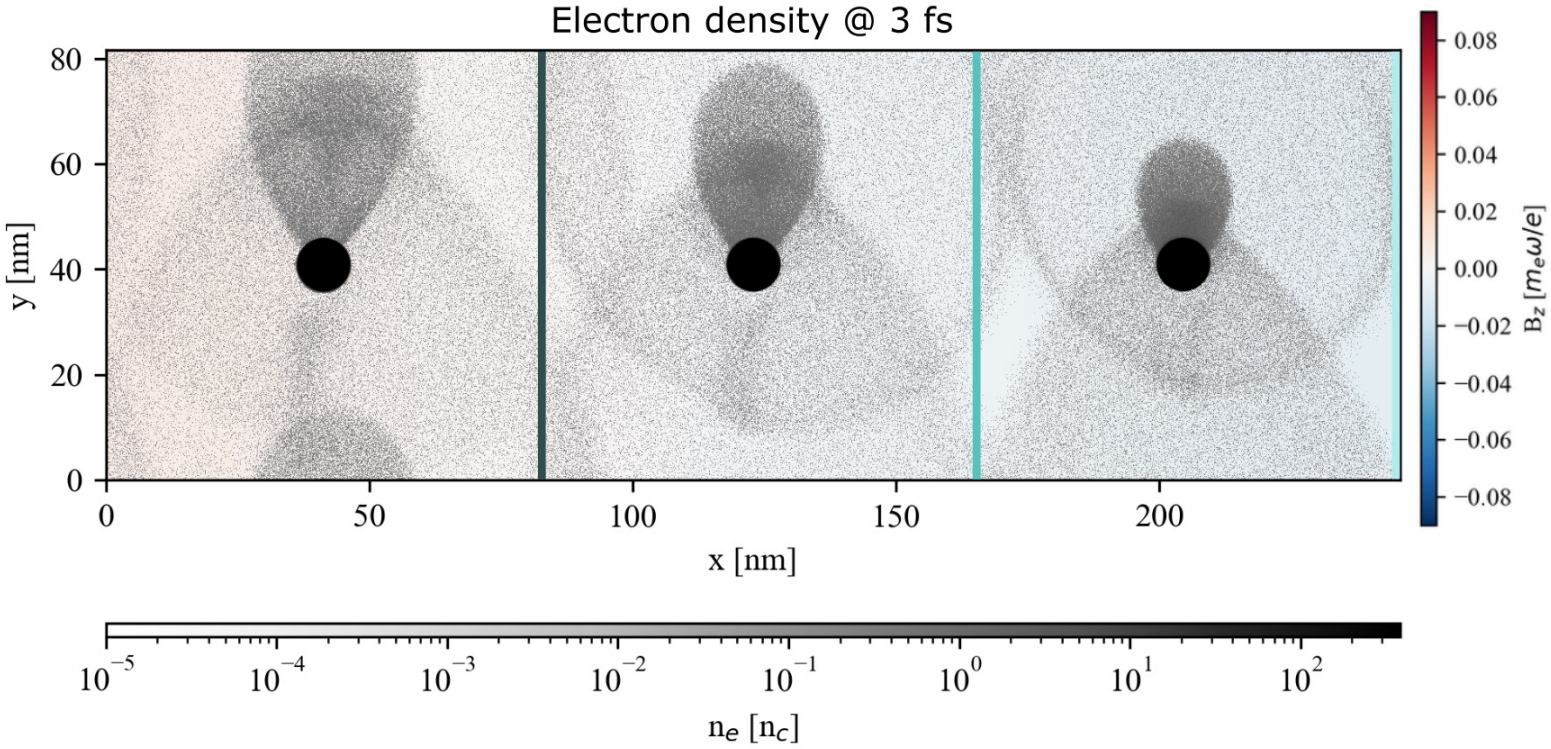
Diffusion-limited cluster-cluster aggregation (DLCCA) process

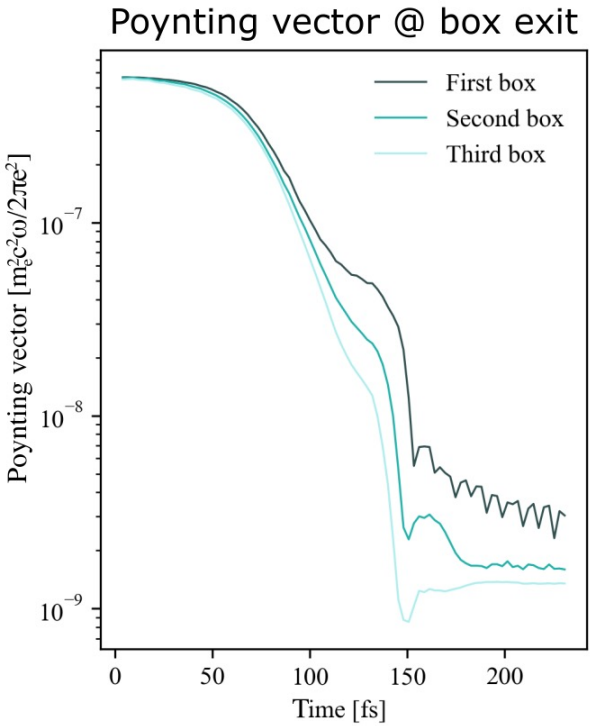
A. Maffini *et al.*, *Plasma Phys. and Contr.Fusion, 68:035007* (2026)
F. Mirani *et al.*, *Physical Review Applied, 24:014017* (2025)
I. Prencipe *et al.*, *New Journal of Physics, 23:093015* (2021)
M. Passoni *et al.*, *Physical Review Acc., 19:061301* (2016)

Effects of nanoparticle radius on mean energy

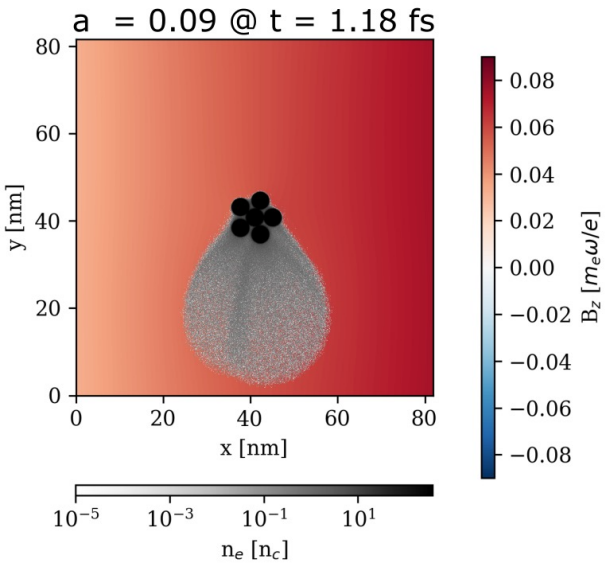


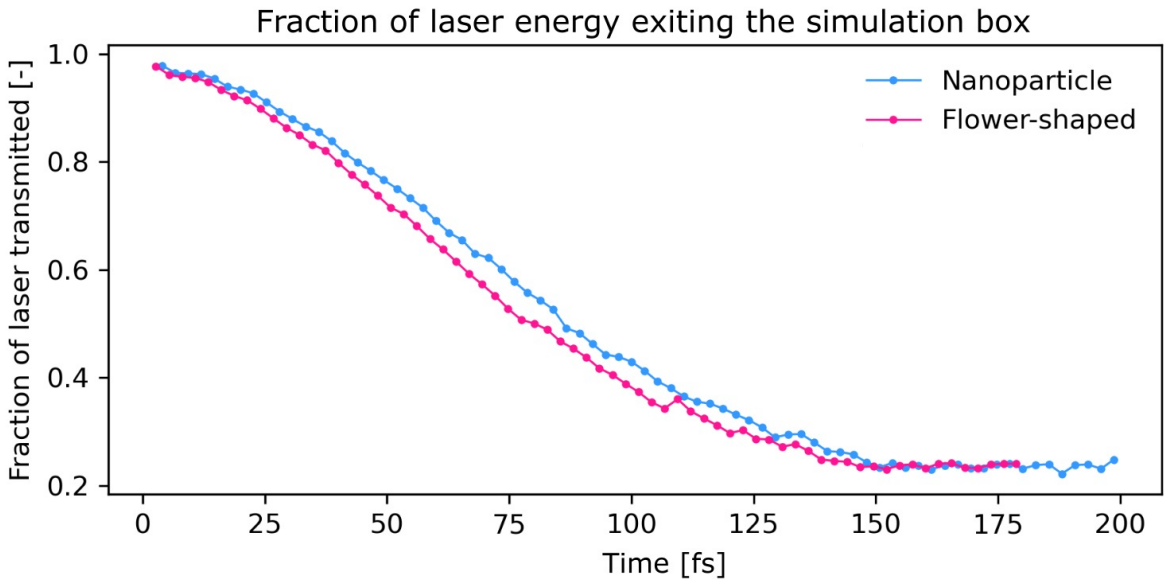
Multi-nanoparticle effects in homogenisation

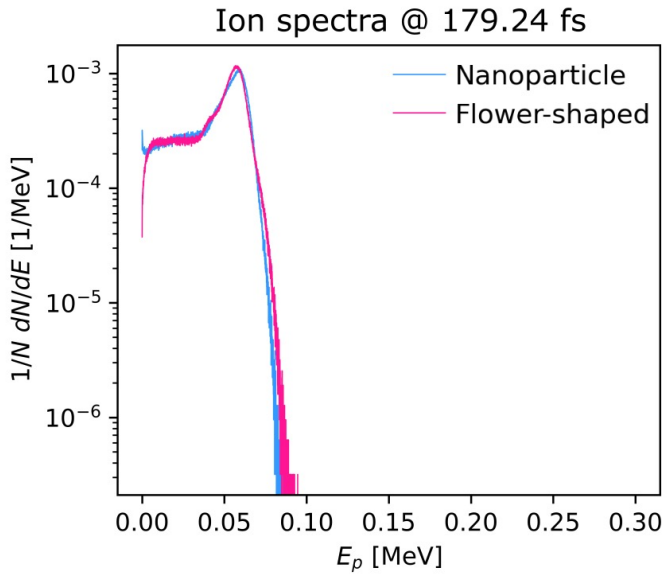




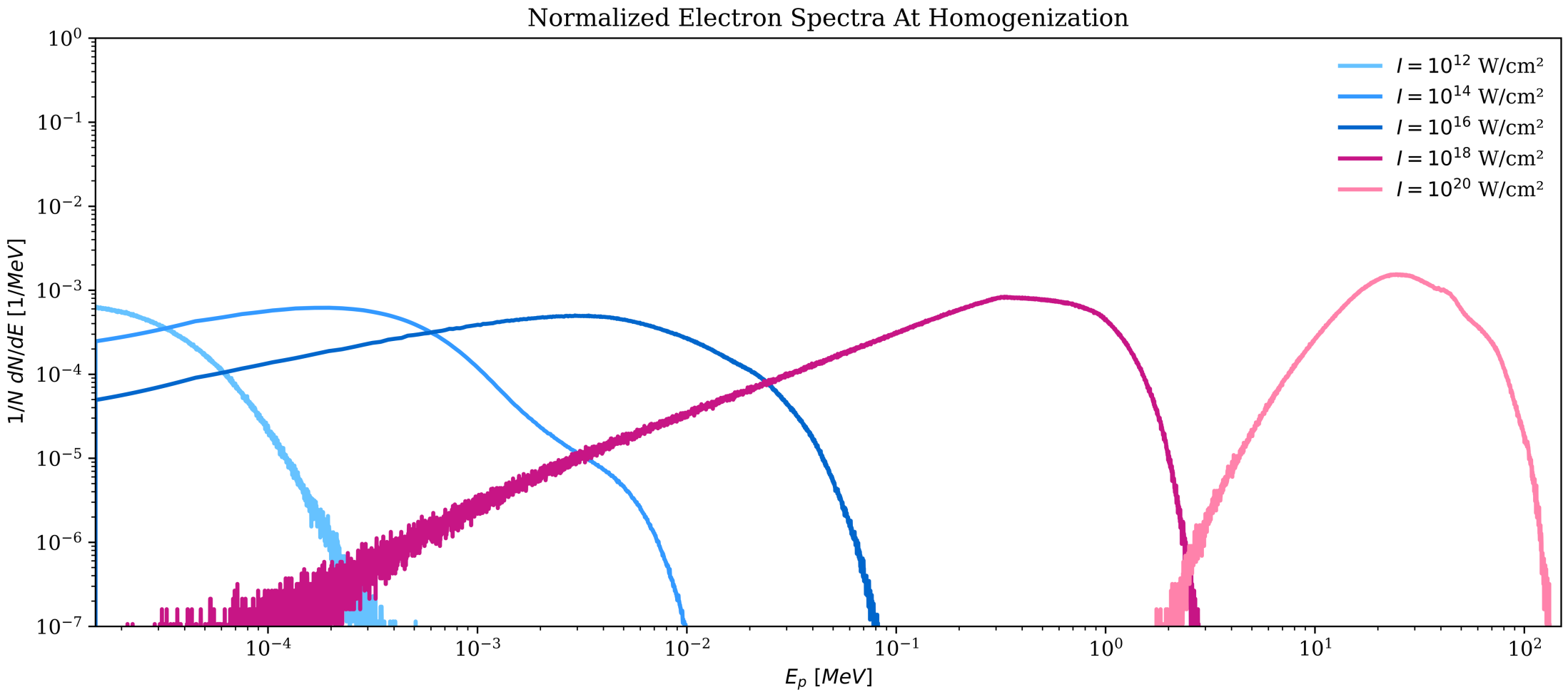
Geometrical effects on homogenisation







Electron spectra with intensity at homogenisation



Effects of laser wavelength on homogenisation