Simulation of intense-laser interaction with nanostructured materials: challenges and perspectives

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Context

Nanofoam-based targets enable **non-linear resonant regimes** of laser-matter interaction owing to their nanostructure and density.

Nanostructure:

- Enables **volumetric particle heating** due to increased propagation of the laser in the material
- Scattering and electron ejection by the laser among the sub-wavelength nanoparticles

Density:

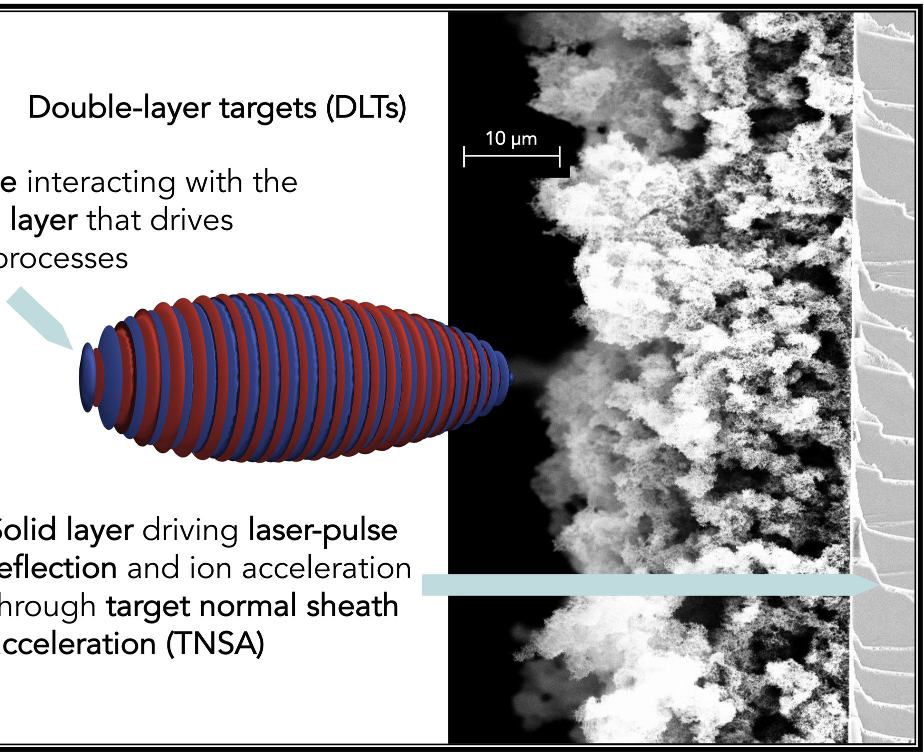
- Between solid and gases (~ mg/cm³) enables **near-critical resonant regime** for commonly used lasers (~ 1-μm wavelength).

Near-critical regime defined by critical density: $n_c = \frac{\epsilon_0 m_e \omega^2}{e^2} \approx \frac{1.11\times10^{21}\ [\mu m^2\ cm^{-3}]}{\lambda^2[\mu m^2]}$

Double-layer targets (DLTs)

Laser pulse interacting with the nanofoam layer that drives resonant processes

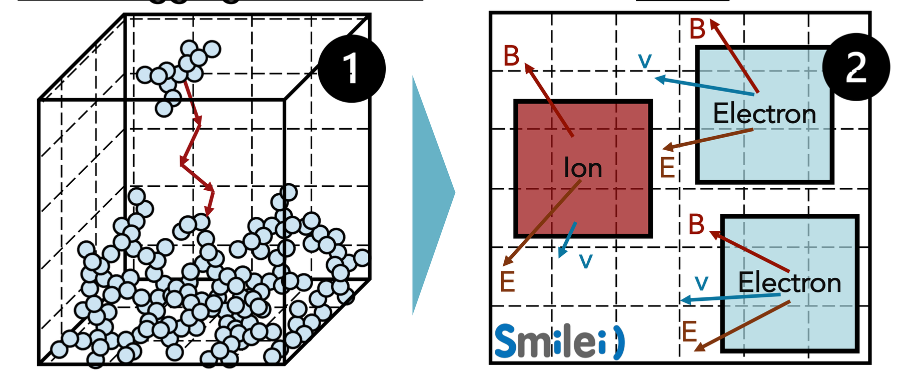
Solid layer driving **laser-pulse reflection** and ion acceleration through **target normal sheath acceleration** (TNSA)



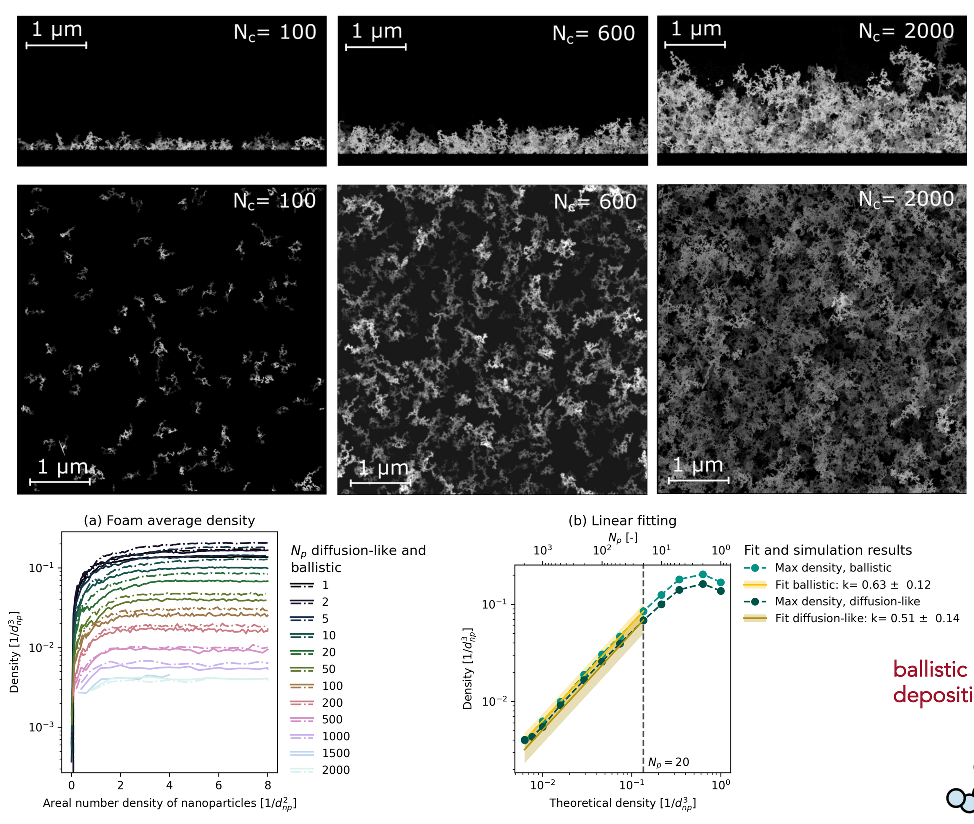
Objectives and methods

- Develop an **accurate** simulation framework for **laser-nanofoam interaction**
- Assessment of the **physical processes** during laser-nanofoam interaction
- Assessment of the **potential** of nanofoam-based targets for physical applications

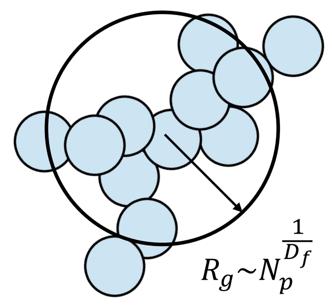
Diffusion-limited cluster-cluster aggregation codes (1) → Particle-in-cell kinetic codes (2)



Simulation of nanofoam aggregation



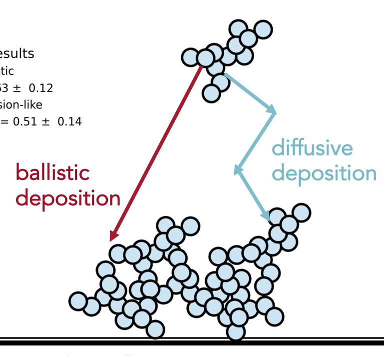
Low-density nanofoams are **fractal** materials. Their density related to the component dimension (R_g) with fractal scaling with number of particles per cluster (N_p):



$R_g \sim N_p^{\frac{1}{D_f}}$ $\rho_f = k\rho_0 N_p^{\frac{3-D_f}{D_f}}$

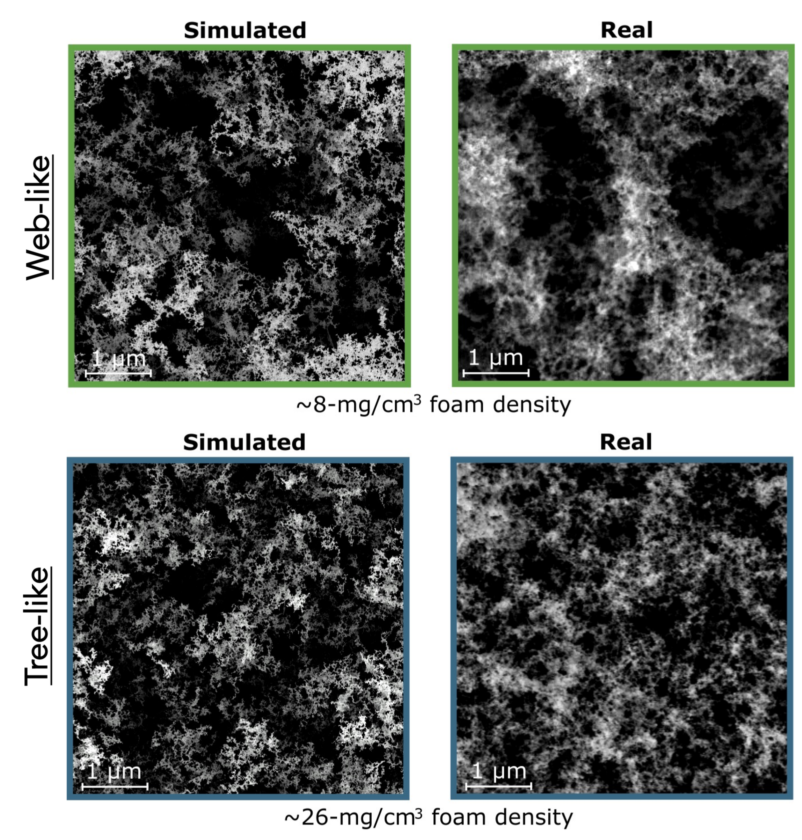
Nanofoams produced @ NanoLab through **pulsed-laser deposition** aggregate in a **snow-fall-like** process.

Description in terms of diffusion-limited cluster-cluster aggregation (DLCCA - D_f = 1.8) of the cluster formation



Simulation of nanofoams @ varying N to characterise k for ballistic and diffusive deposition

Ability to simulate nanofoams of **desired density and thickness** in the **range of validity** of the fractal scaling!



Comparable void dimension between simulated and experimentally produced nanofoams!

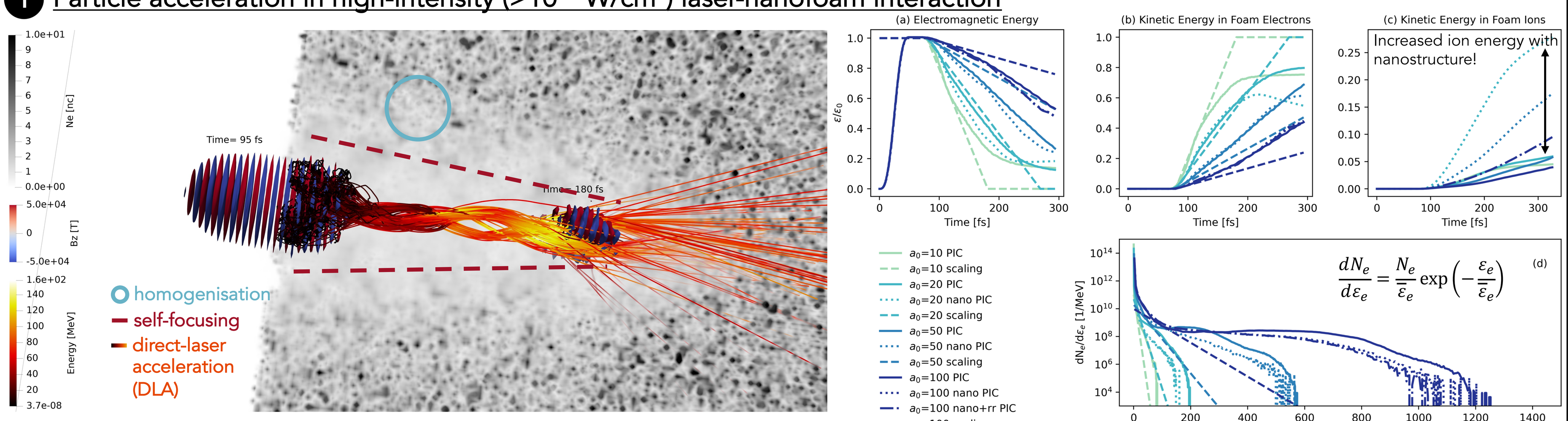
8-mg/cm³	26-mg/cm³
Approximately 4.5 μm for the simulated and 5.5 μm for the experimental foam	Approximately 1.5 μm for the simulated and 2.5 μm for the experimental foam
Approximately 1.5 n_c for homogenised totally ionised foam @ 0.8-μm wavelength	Approximately 4.5 n_c for homogenised totally ionised foam @ 0.8-μm wavelength

How do we increase the agreement?

Moving from monodispersed distribution for N_p, to more realistic distributions (i.e., **exponential** distribution for PLD with ns-laser pulses and **two-species** distribution for PLD with fs-laser pulses)

Particle acceleration and generation in laser-nanofoam interaction

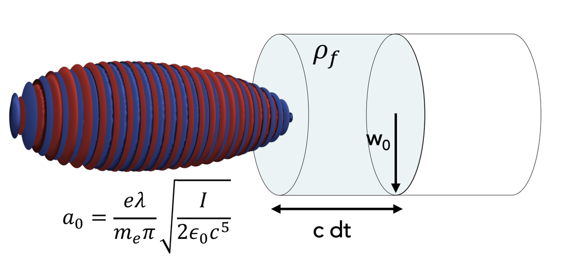
1 Particle acceleration in high-intensity (>10¹⁸ W/cm²) laser-nanofoam interaction



Completely ionised **graphite non-collisional-plasma** from DLCCA simulation (60-μm-thick, 8-mg/cm³ density)

Strongly magnetised plasma channel driving electron betatron oscillation. High energy spectrum tail due to direct laser acceleration.

Approximated **energy absorption** evolution with **ponderomotive scaling** valid for **low laser intensity**

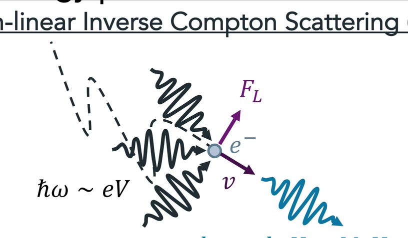


$a_0 = \frac{e\lambda}{m_e\pi}\sqrt{\frac{I}{2\epsilon_0 c^5}}$

$$\begin{cases} \frac{d\varepsilon_l}{dt} = -\bar{\varepsilon}_e\frac{dN_e(t)}{dt} \\ \frac{dN_e}{dt} = \pi w_0^2 \rho_f c \\ \bar{\varepsilon}_e = \left(\sqrt{1+a_0^2/2}-1\right)m_e c^2 \end{cases}$$

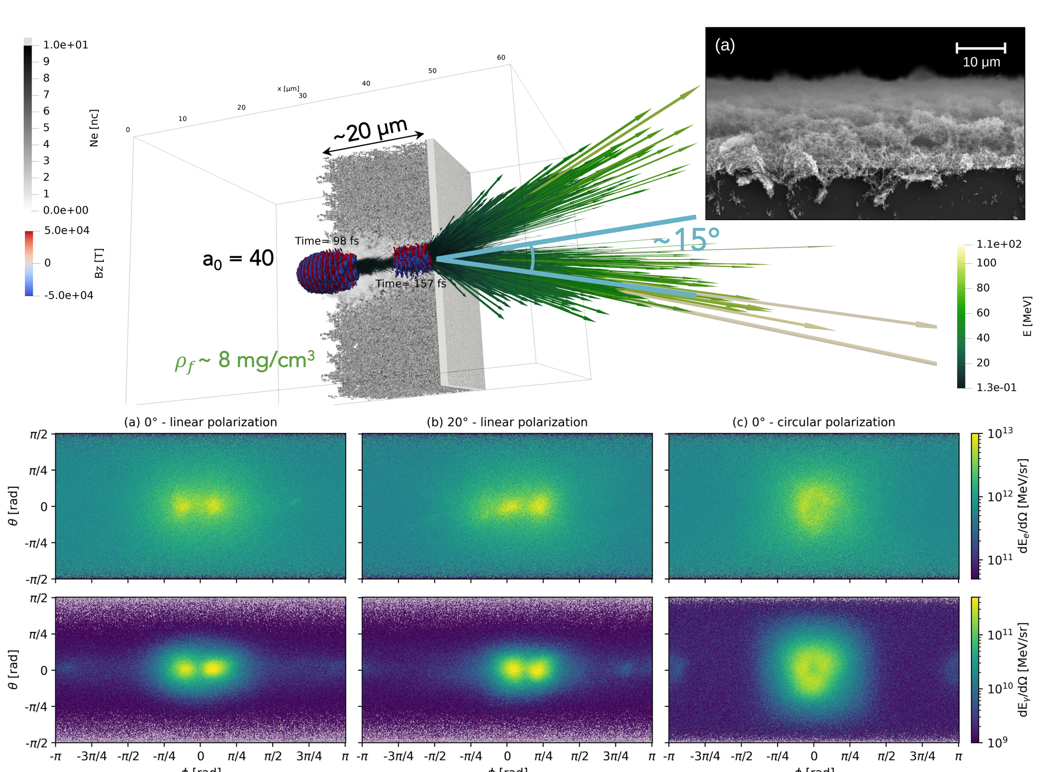
2 High-energy photons in laser-DLT interaction

Non-linear Inverse Compton Scattering (NICS)

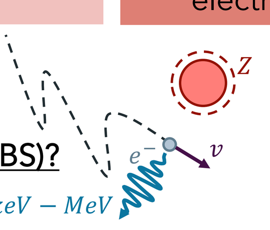


Head-on collisions between reflected laser and energetic electrons maximising NICS

NICS emission reflects electron betatron oscillation. Max. emission @ 15° from laser propagation (max. electron velocity)



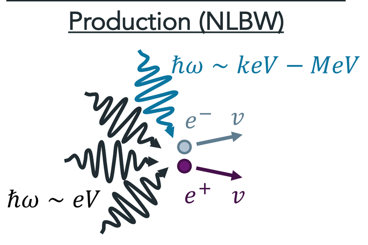
What about bremsstrahlung (BS)?



DLA electrons as seed in pitcher-catcher configurations!

3 Pair production through laser-DLT interaction

Non-linear Breit- Wheeler Pair Production (NLBW)

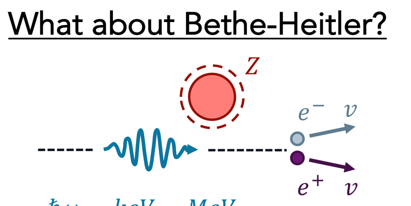


Head-on collisions between reflected laser and NICS photons

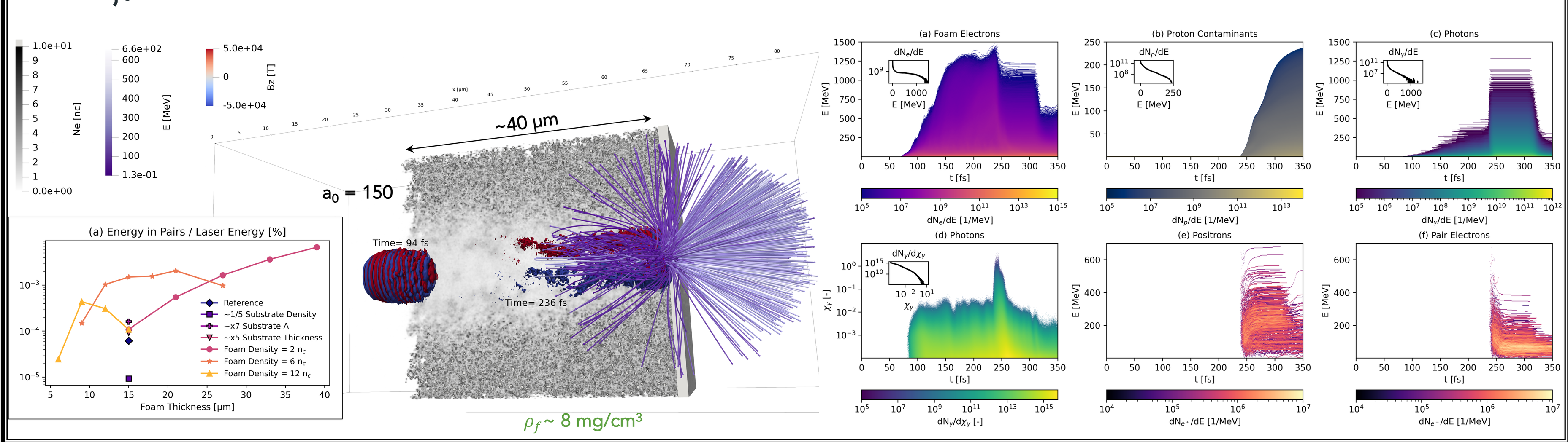
NLBW @ currently achievable laser intensity (~ 10²² W/cm²)

Acceleration of positrons through TNSA

What about Bethe-Heitler?



BS and NICS seed in pitcher-catcher!

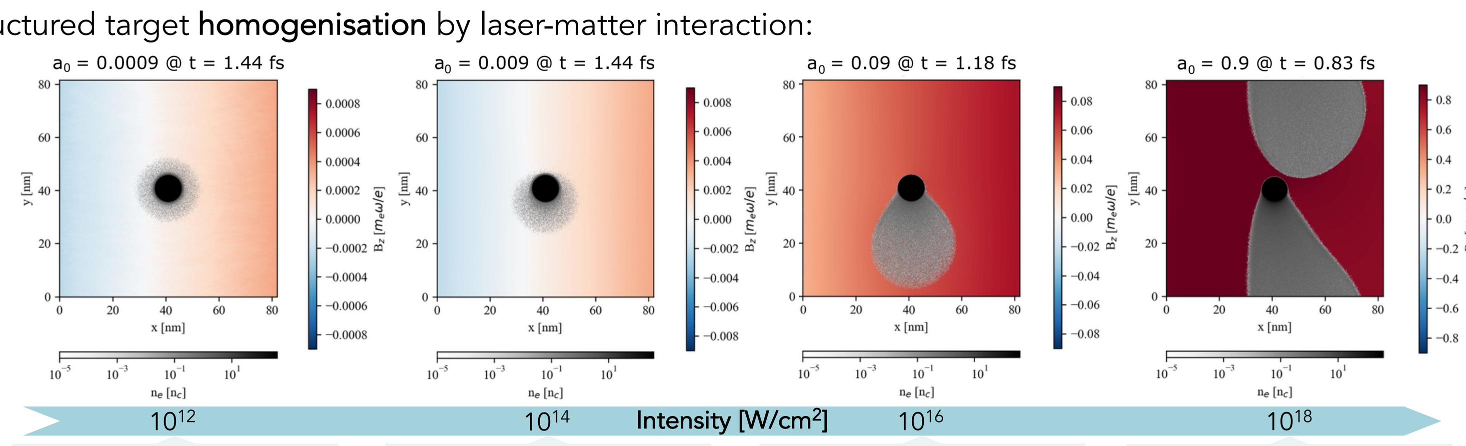


Nanofoam homogenisation by laser-matter interaction

Investigation of nanostructured target **homogenisation** by laser-matter interaction:

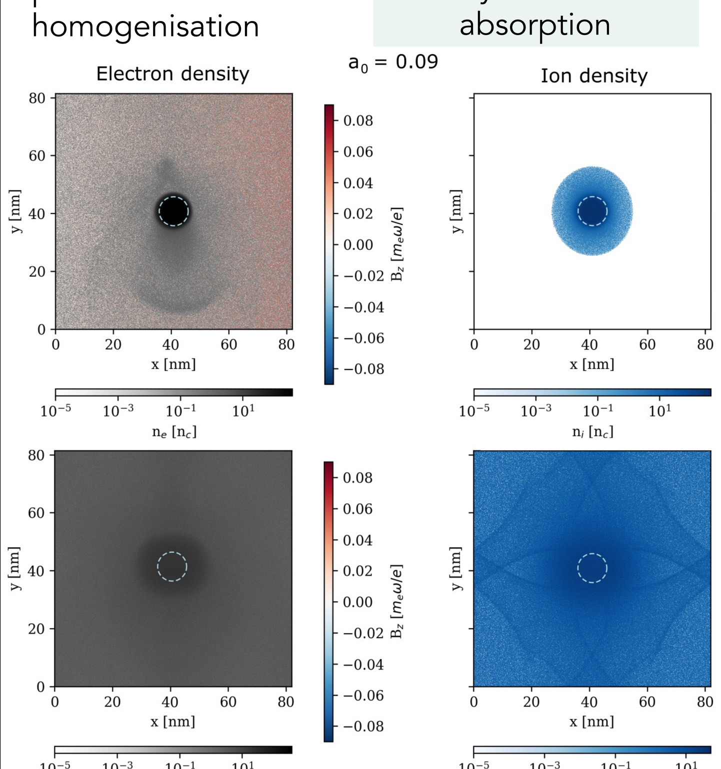
Completely ionised **graphite collisional-plasma nanoparticle** in square box with periodic boundary conditions (10-nm diameter, 26-mg/cm³ homogenised density)

Laser as an 800-nm plane wave until homogenisation

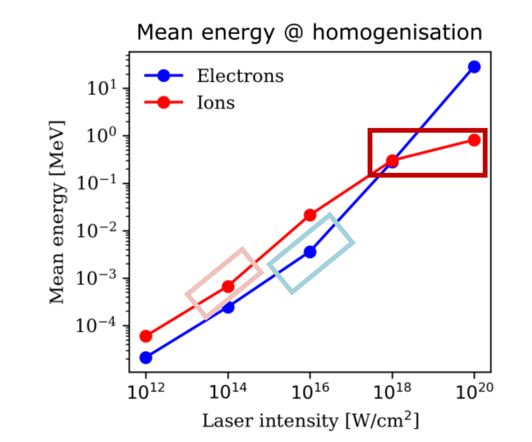


Intensity [W/cm²]: 10¹² – 10¹⁴ – 10¹⁶ – 10¹⁸

Only collisional absorption	Electric field starts to push out electrons	Non-collisional absorption increases	8-like trajectories due to magnetic field



1. Electrons generate uniform background, charge separation drives partial ion Coulomb explosion
2. Homogenisation and absorption of laser energy via collisions

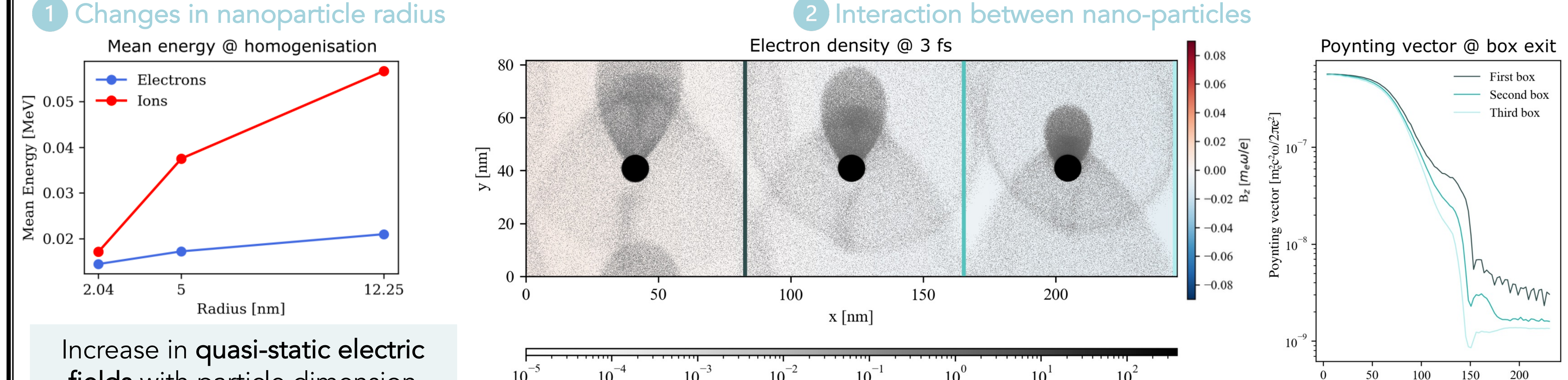


- Slope change indicating additional electron heating (v×B)
- Slope change indicating additional ion heating
- Saturation of ion heating indicating Coulomb explosion

What about dimension and geometry effects?

1 Changes in nanoparticle radius

2 Interaction between nano-particles



Increase in **quasi-static electric fields** with particle dimension

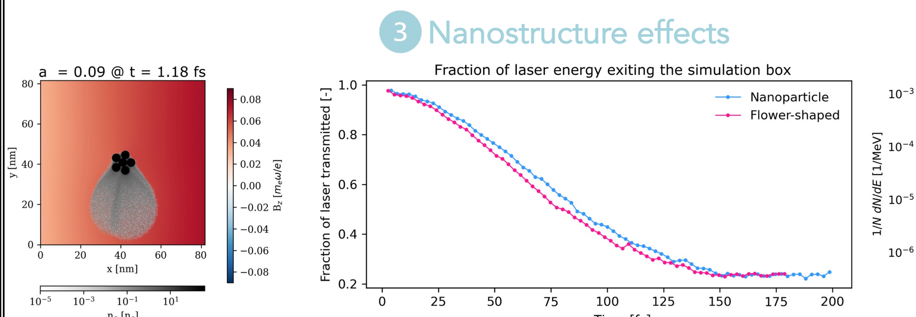
Increase of **particle energy** and homogenisation time

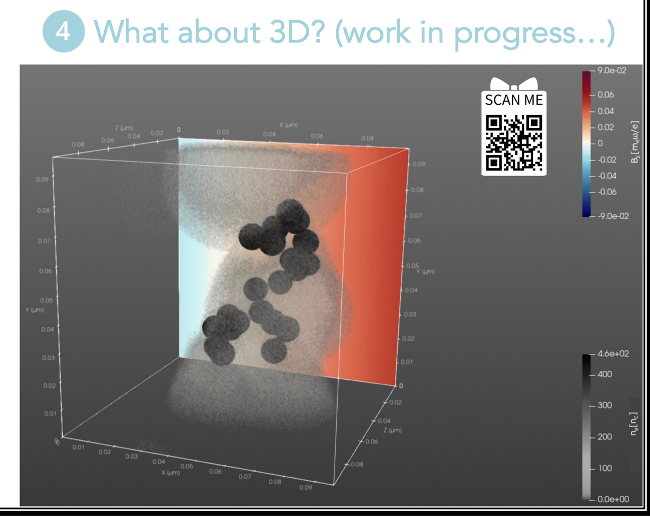
Temporal shift in the electron oscillation, but negligible absorption differences

Reduction of **laser energy flux** during propagation mostly at homogenisation

3 Nanostructure effects

4 What about 3D? (work in progress...)





At constant mass amount, the presence of a nanostructure **increases energy absorption** by the plasma due to geometrical effects

Non-equilibrium ion spectra showing similar peaks and suggesting **similar Coulomb explosion** for both geometries

Conclusions and future developments

Integrating realistic DLCCA nanostructure in PIC simulations enables the study of physical processes due to the presence of a non-homogeneous material made of sub-wavelength nanoparticles

Using nanofoam-based DLTs allows for the observation of strong field QED effects thanks to the intertwining between laser reflection on solid foils and efficient electron acceleration in near-critical nanofoams

Studying **nanofoam-based targets** for efficient high-energy photon and positron generation

Integration of physical modelling of **nanofoam homogenisation** in fluid codes for prepulse and inertial-fusion-relevant simulations

References

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