High intensity laser interaction with nanostructured targets:

a possible route for enhanced laser-driven ion sources

POLITECNICO
MILANO 1863

Luca Fedeli

Ningbo, 24/10/2018

POLITECNICO
MILANO 1863

The ENSURE group at Politecnico di Milano

Matteo Passoni
Associate professor

ERC-2014-CoG
No.647554 **ENSURE**

ERC-PoC **INTER**

We are interested in:

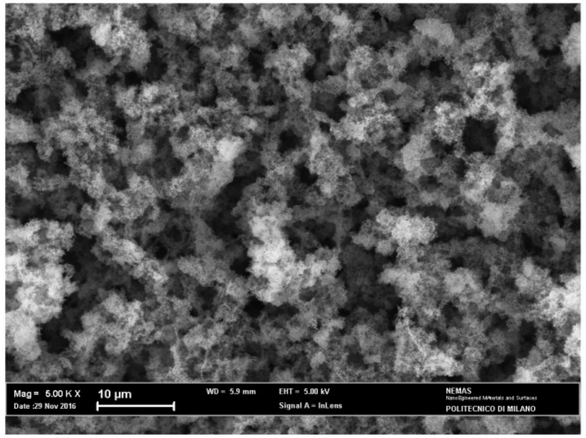
- Laser-driven sources
- Materials and nuclear science applications of laser-driven sources
- Advanced targetry

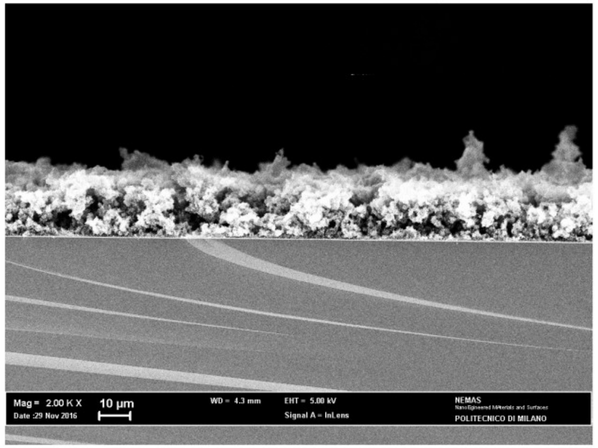
Collaborations with:

HZDR
SourceLAB
OSAKA UNIVERSITY
CLPU
GIST Gwangju Institute of Science and Technology

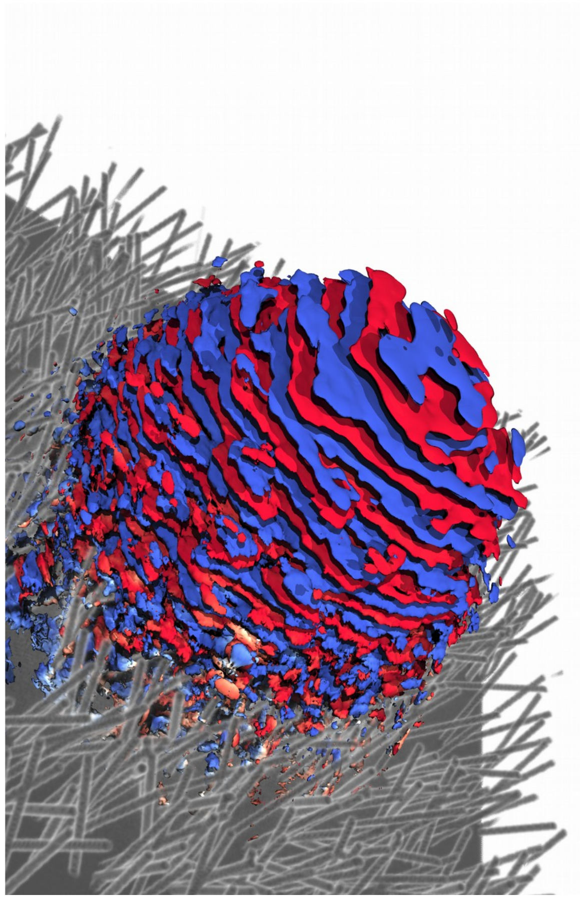
High intensity laser interaction with nanostructured targets:

a possible route for enhanced laser-driven ion sources

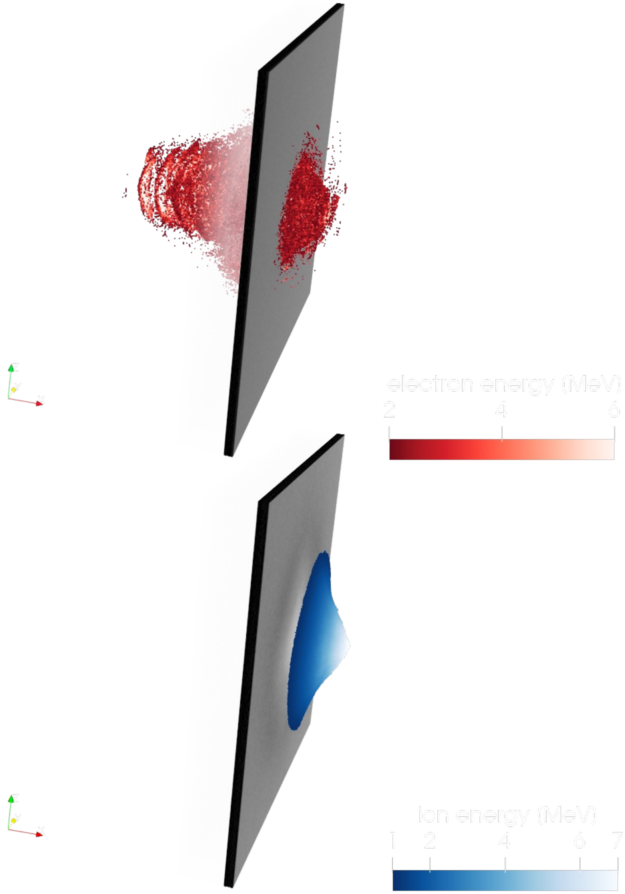




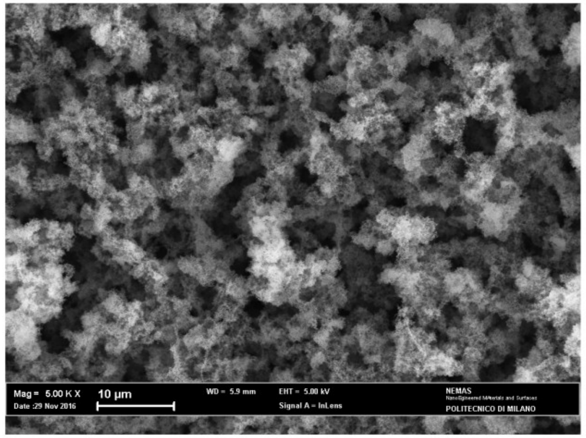
Nanostructured low-density materials

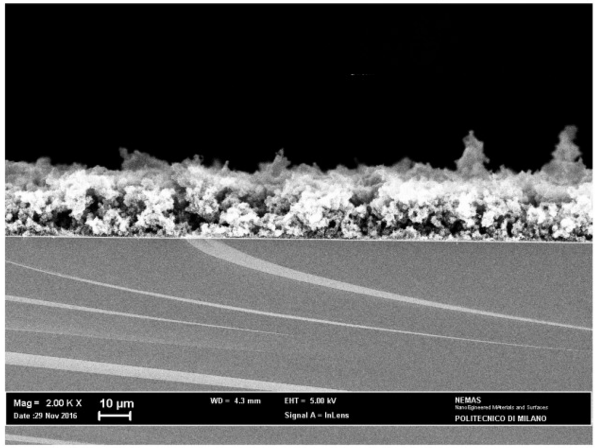


Modeling of laser interaction with nanostructures

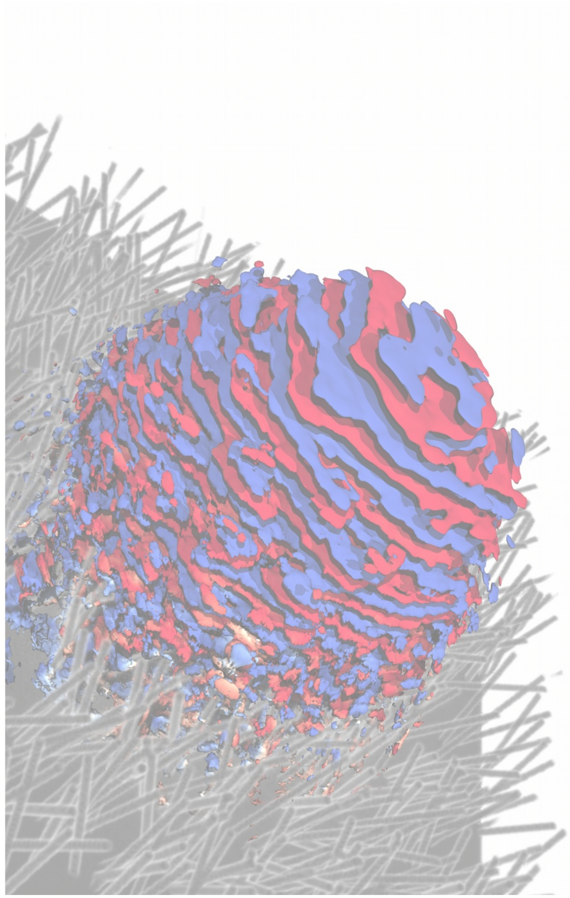


Enhanced laser-driven ion acceleration

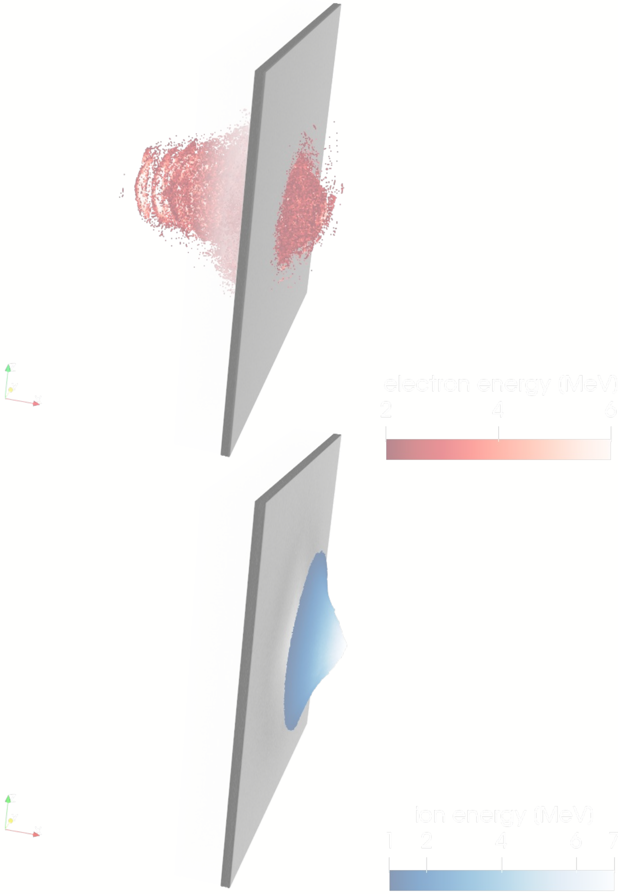




Nanostructured low-density materials

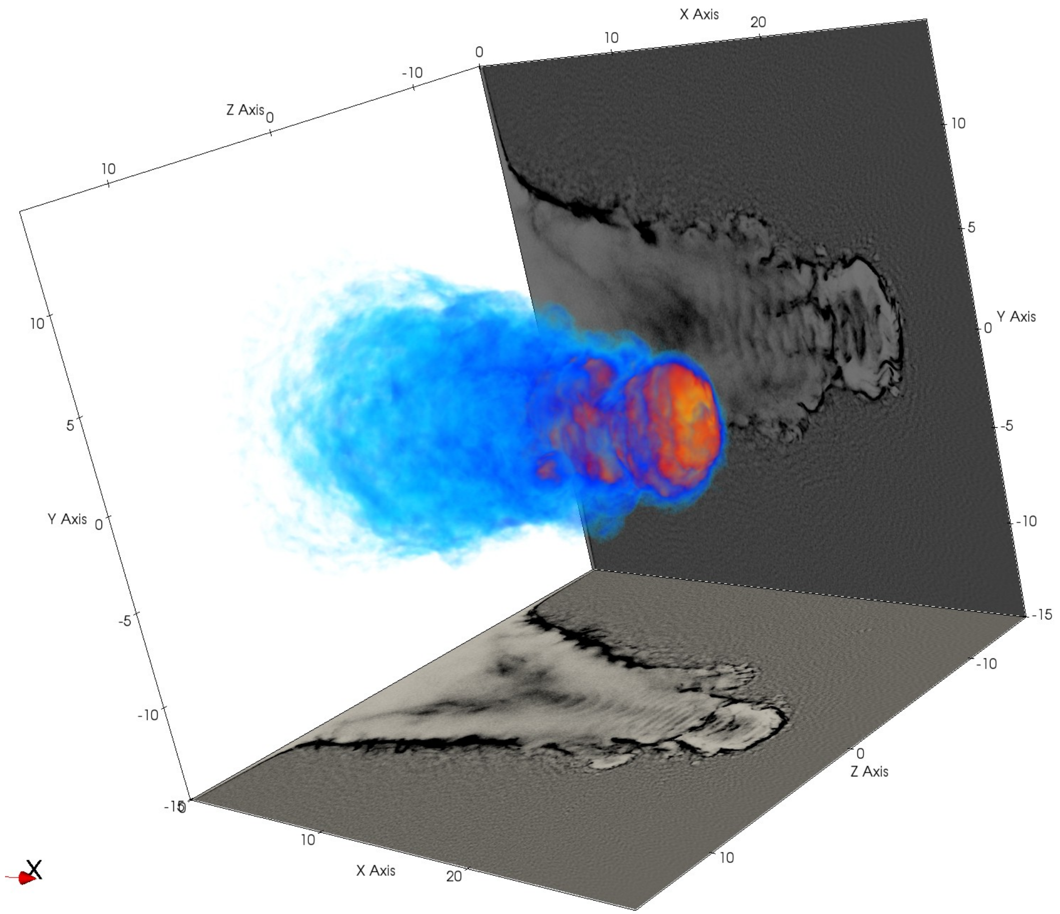


Modeling of laser interaction with nanostructures



Enhanced laser-driven ion acceleration

Near-critical plasmas are of great interest for a number of applications



- Laboratory astrophysics
- Enhanced ion acceleration
- γ-ray sources
- Inertial confinement fusion
- Electron acceleration
- High-order harmonic generation
- [...]

For a Ti:Sapphire laser and A/Z~2, **near-critical** density means a **very low mass density**

$$\rho_c(\lambda) = \frac{1.87}{\lambda^2[\mu m]}\left(\frac{A}{Z}\right)\frac{mg}{cm^3} \Rightarrow \rho_c(0.8\,\mu m) \approx 6\,\frac{mg}{cm^3}$$

For a Ti:Sapphire laser and A/Z~2, **near-critical** density means a **very low mass density**

$$\rho_c(\lambda) = \frac{1.87}{\lambda^2[\mu m]}\left(\frac{A}{Z}\right)\frac{mg}{cm^3} \Rightarrow \boxed{\rho_c(0.8\,\mu m) \approx 6\,\frac{mg}{cm^3}}$$

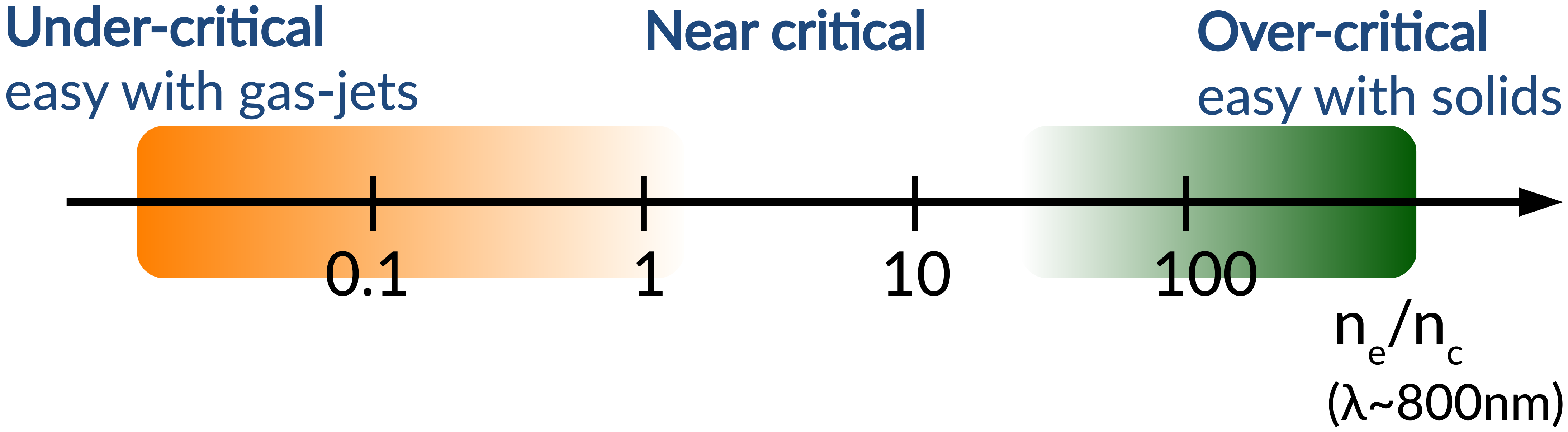
For a Ti:Sapphire laser and A/Z~2, **near-critical** density means a **very low mass density**

$$\rho_c(\lambda) = \frac{1.87}{\lambda^2[\mu m]}\left(\frac{A}{Z}\right)\frac{mg}{cm^3} \Rightarrow \boxed{\rho_c(0.8\,\mu m) \approx 6\,\frac{mg}{cm^3}}$$

AIR ~ 1.2 mg / cm^3

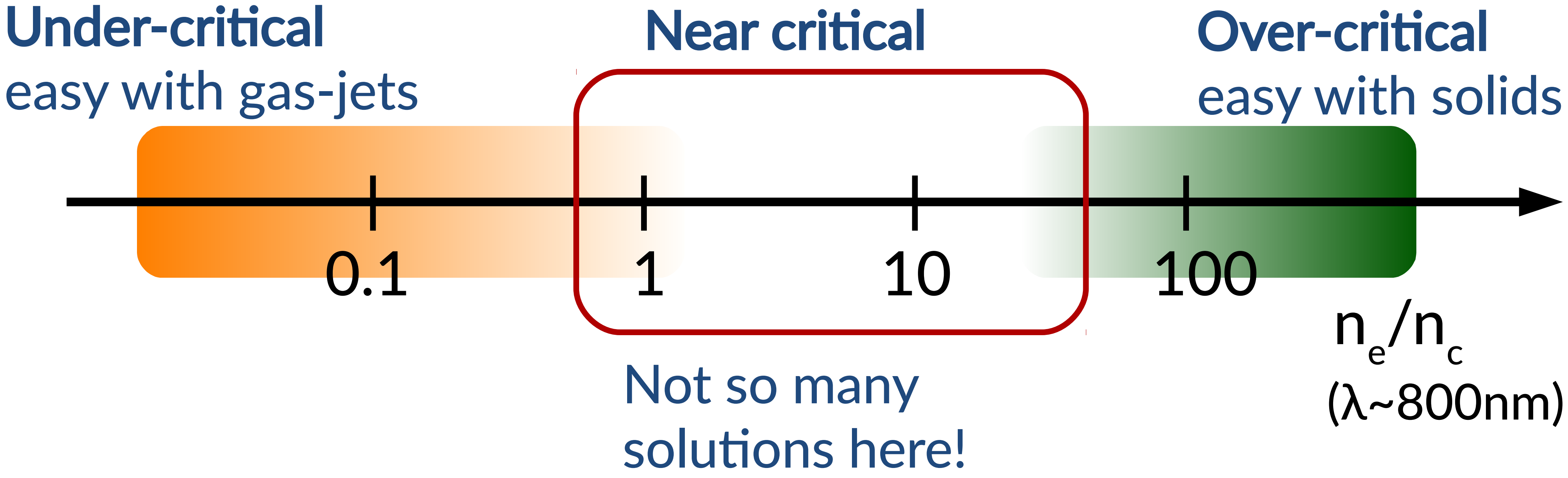
WATER 1000 mg / cm^3

“Easy” to have under-critical or over-critical plasmas



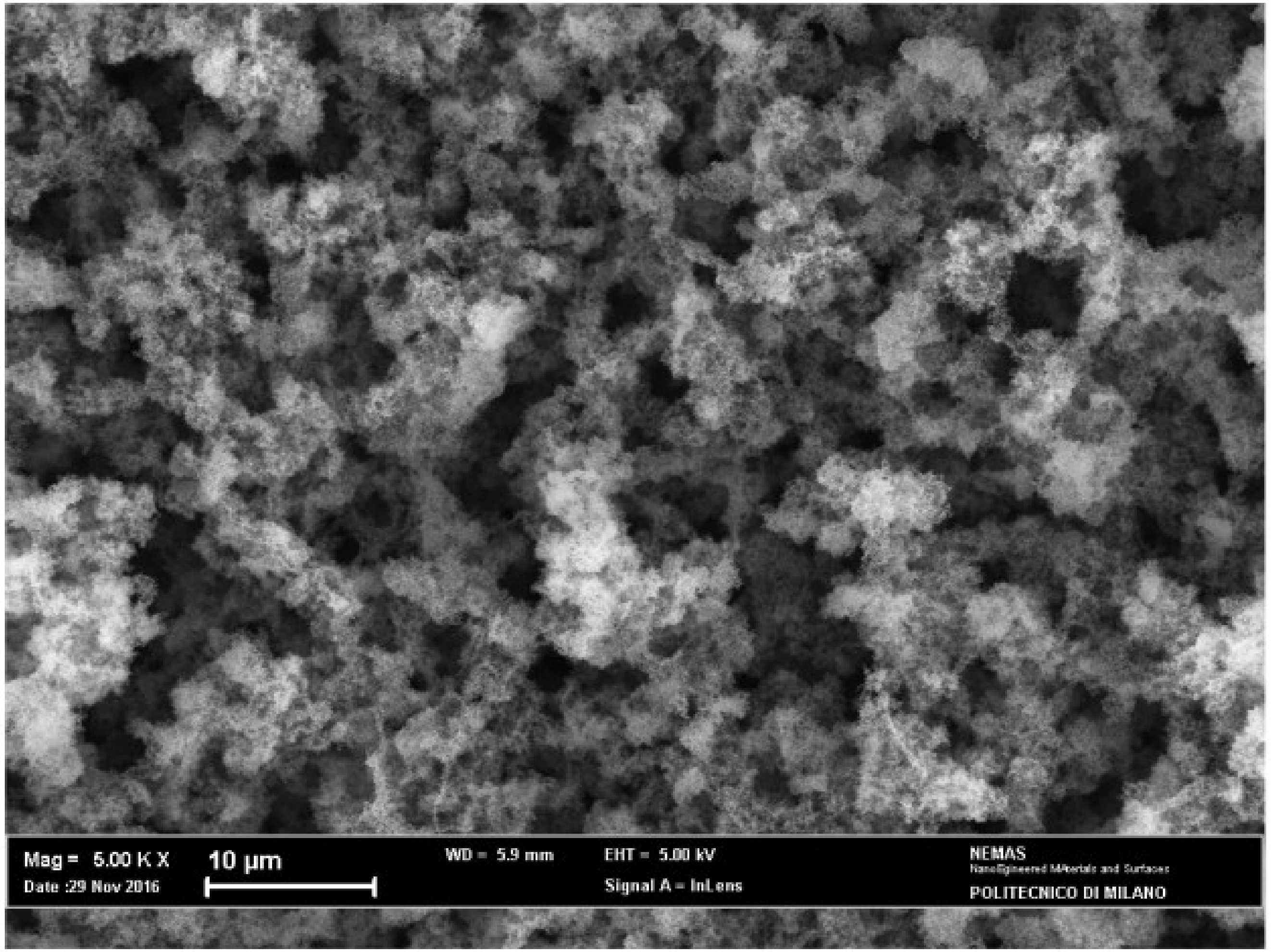
I.Prencipe et al. High Power Laser Science and Engineering, Vol. 5, e17 (2017)

There is a "targetry" gap for near-critical densities

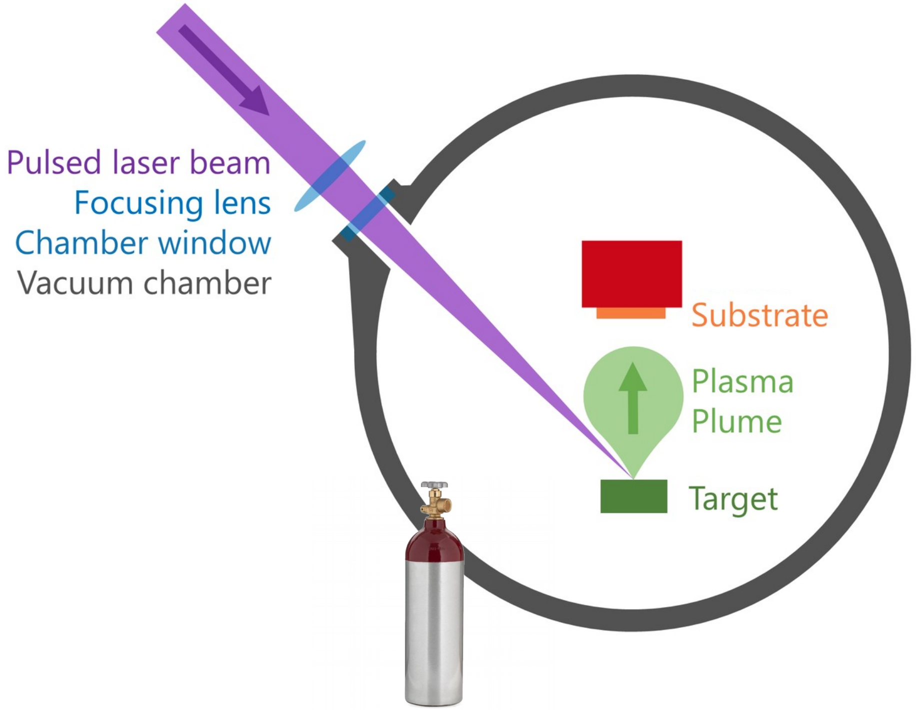


I.Prencipe et al. High Power Laser Science and Engineering, Vol. 5, e17 (2017)

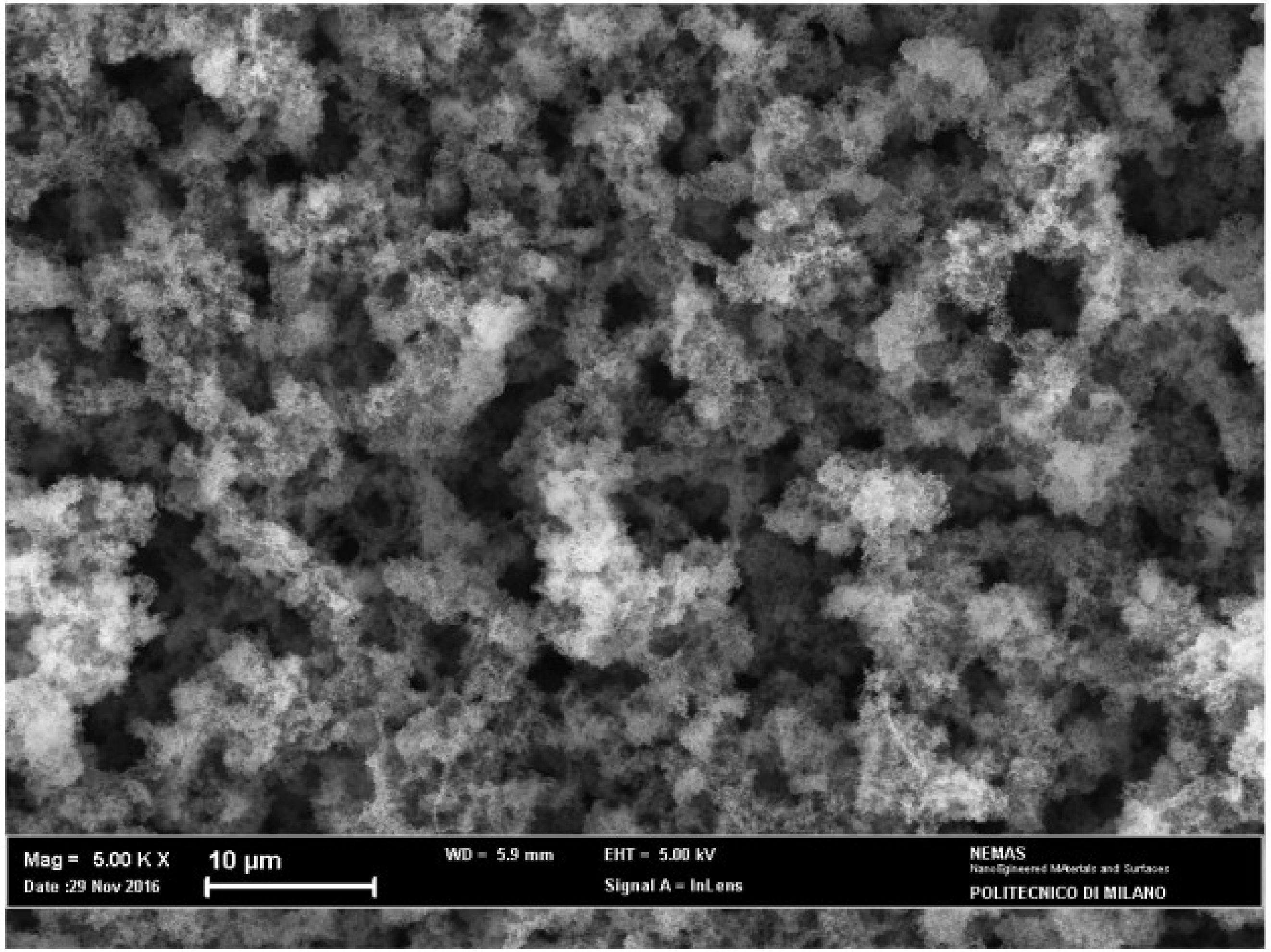
Nanostructured Carbon foams with Pulsed Laser Deposition



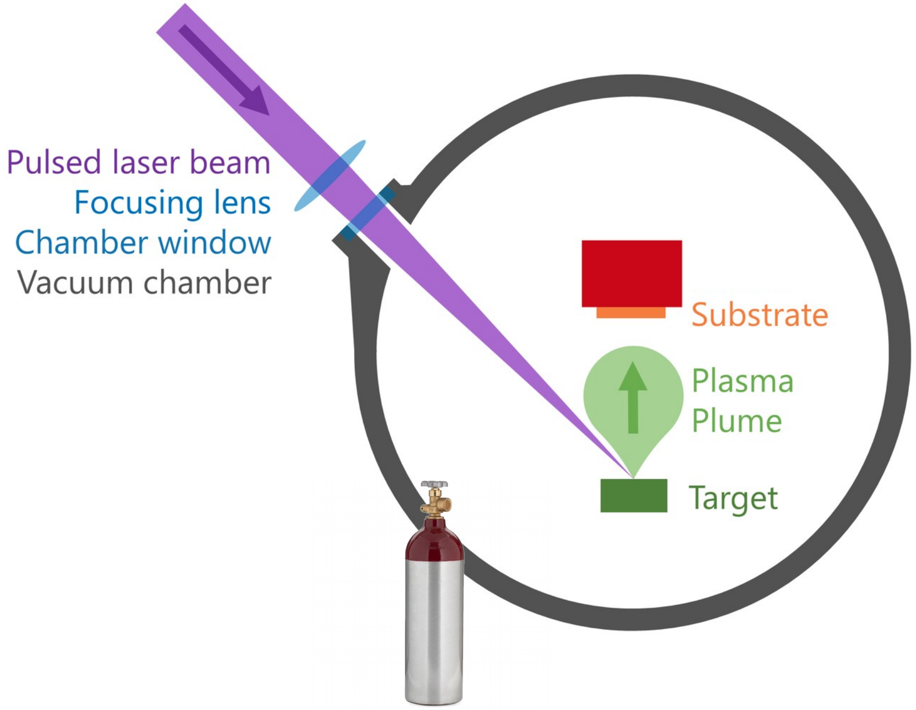
A. Zani et al. Carbon. 56: 358–365 (2013)



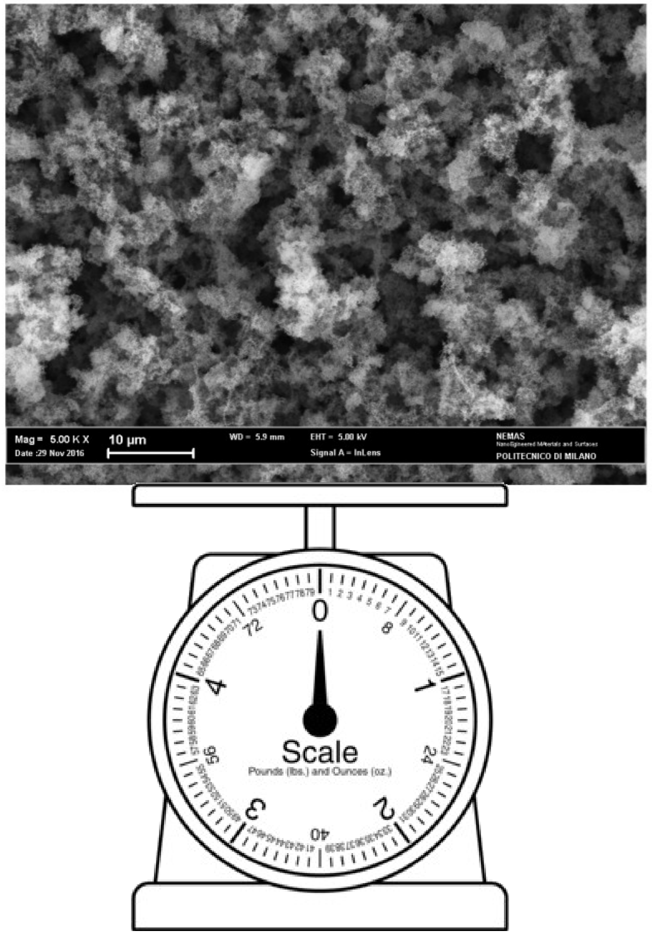
Very porous structures. Locally at the solid density but with many voids.



A. Zani et al. Carbon. 56: 358–365 (2013)



Nanostructured foams can have a **very low density**

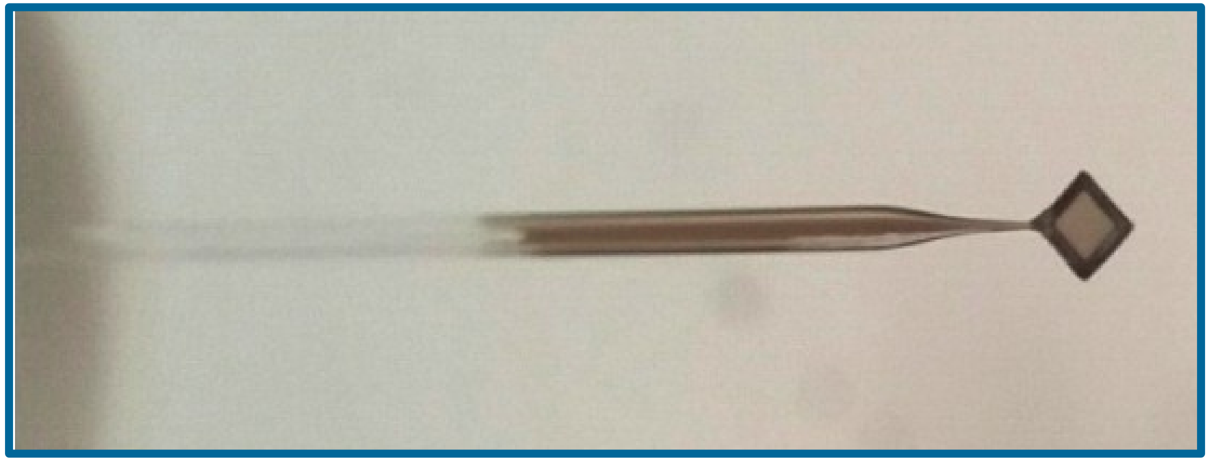


Lowest achievable density **~ 10 mg/cm³**

Near-critical density!

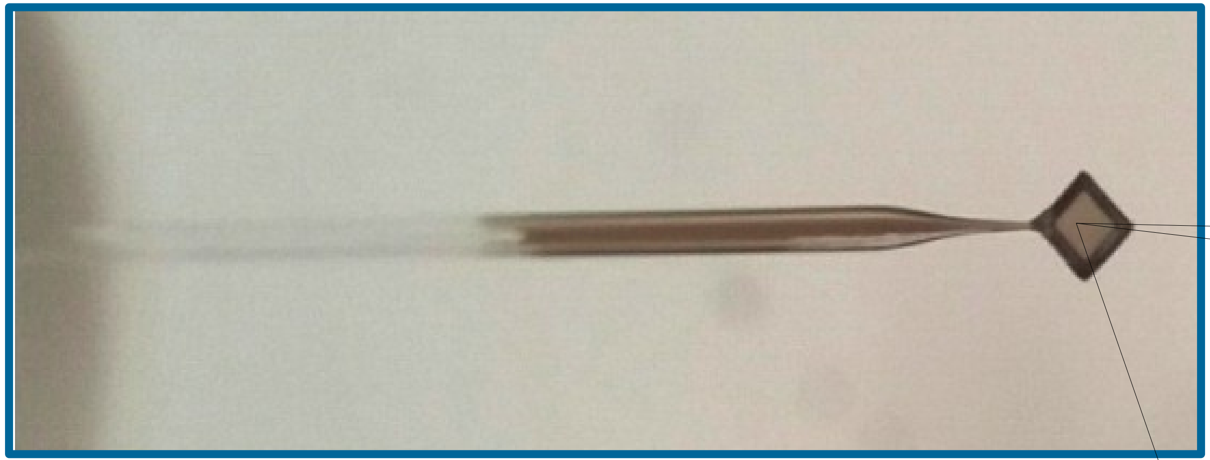
$$\rho_c(0.8\,\mu m) \approx 6\,\frac{mg}{cm^3}$$

Great flexibility: deposition on virtually any substrate!

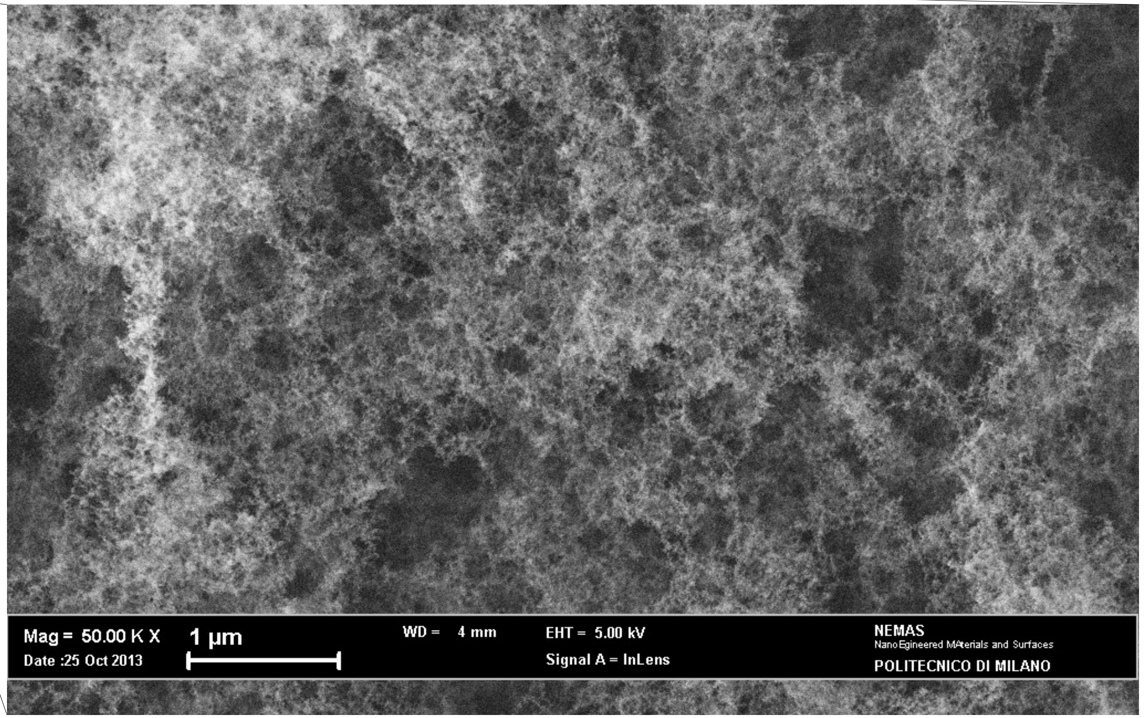


200 nm thin CH substrate

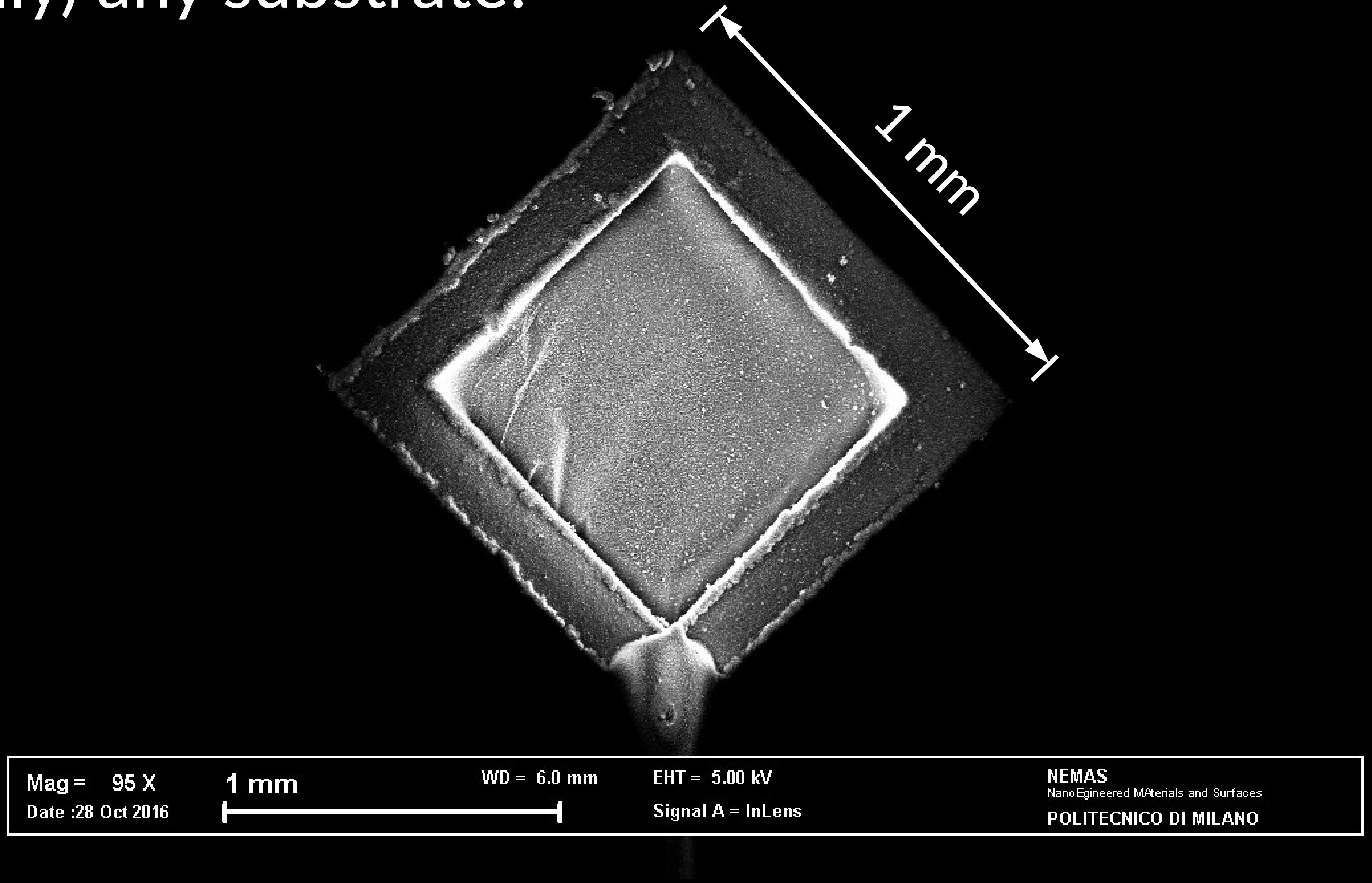
Great flexibility: deposition on virtually any substrate!



200 nm thin CH substrate



Great flexibility: deposition on (virtually) any substrate!



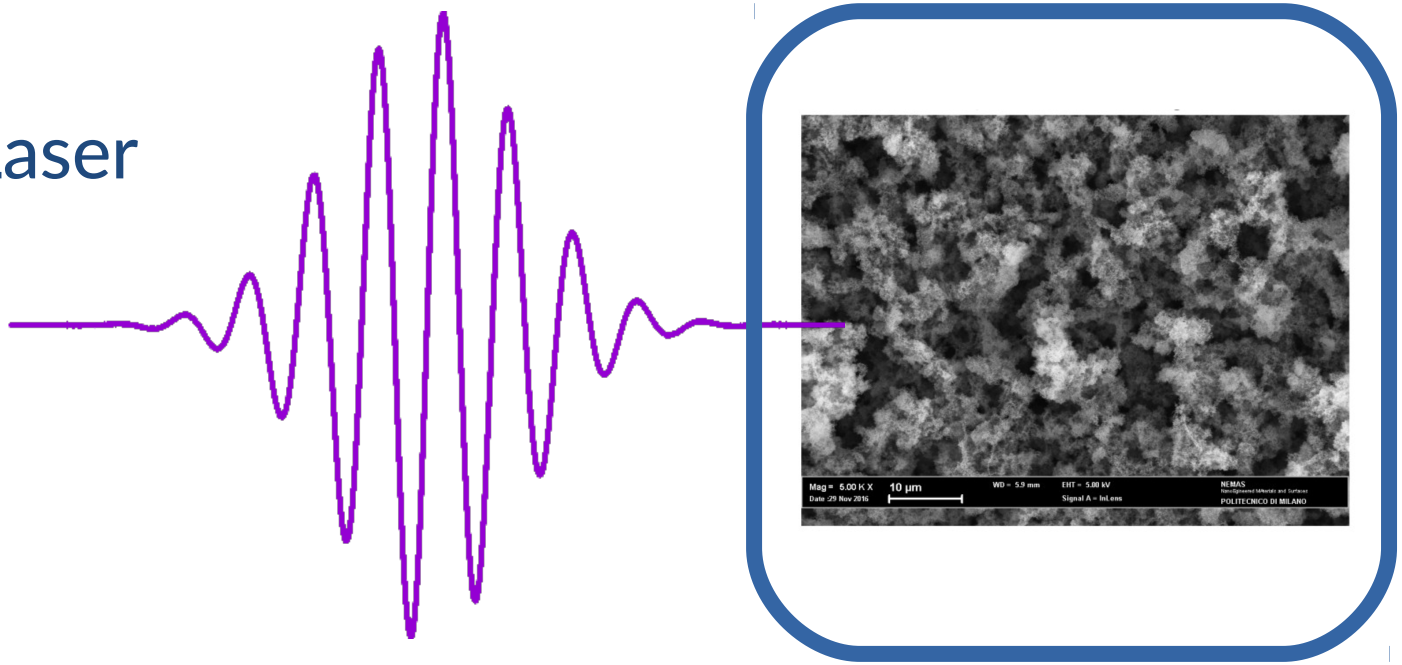
Great flexibility: density gradients!

~ 10 mg/cm^3

~ 150 mg/cm^3

Solid substrate

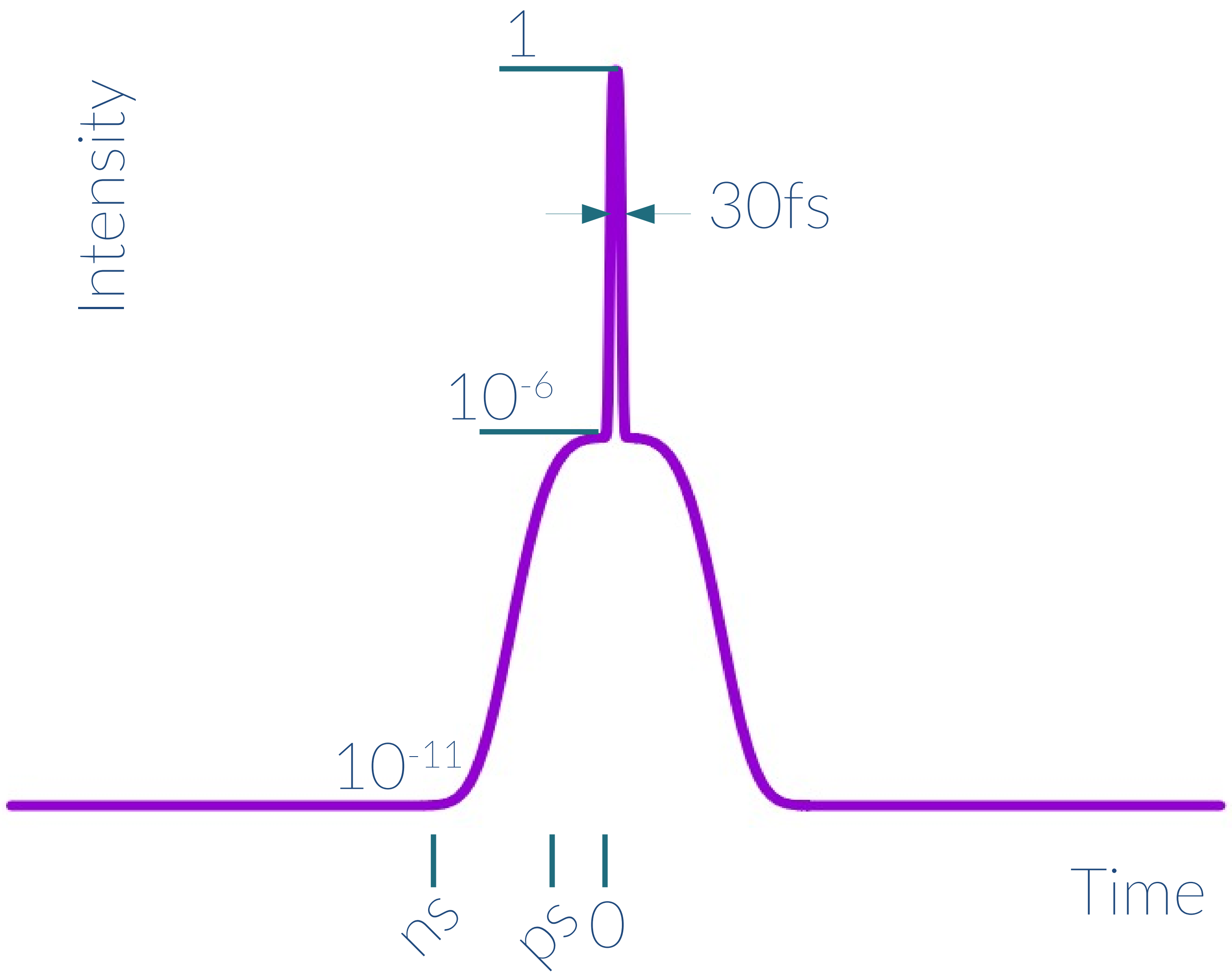
Laser



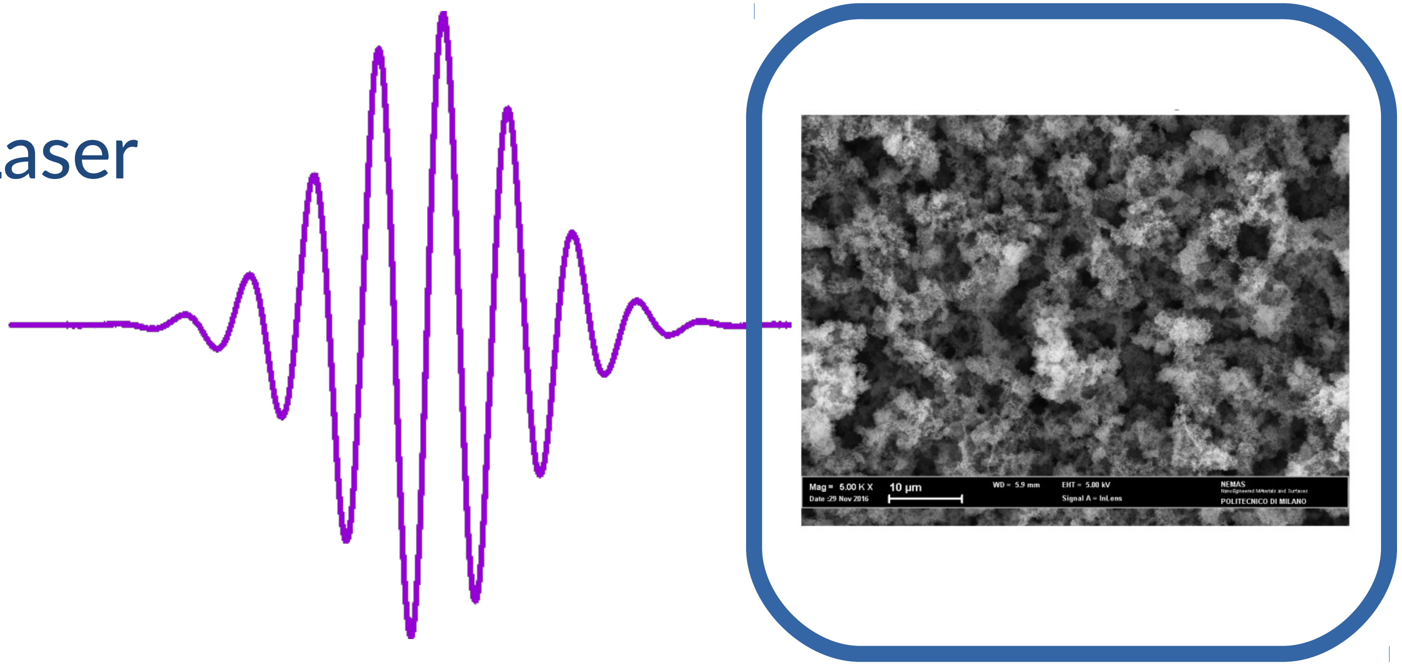
Near-critical plasma

Foams can be used as near-critical targets

Very high laser contrast:
nanostructures might survive the interaction



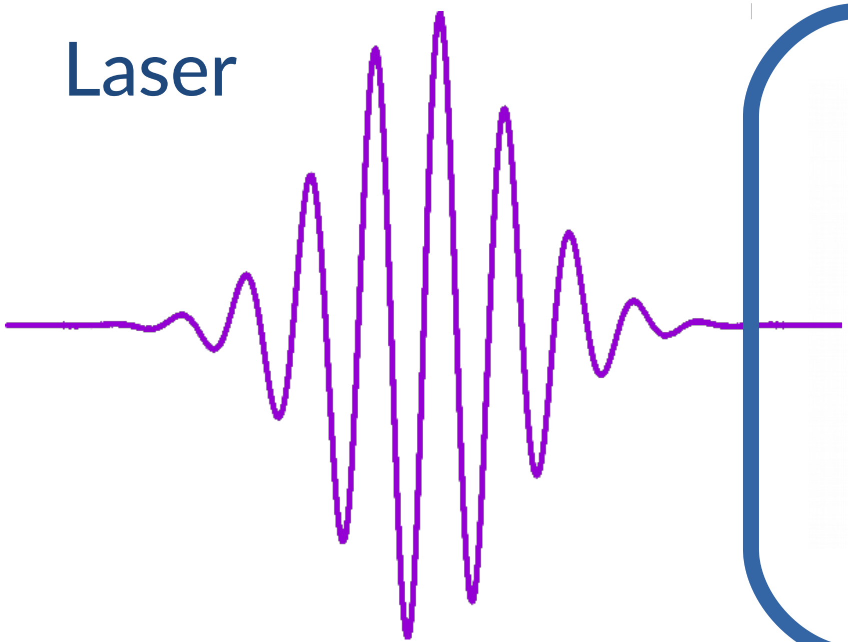
Laser

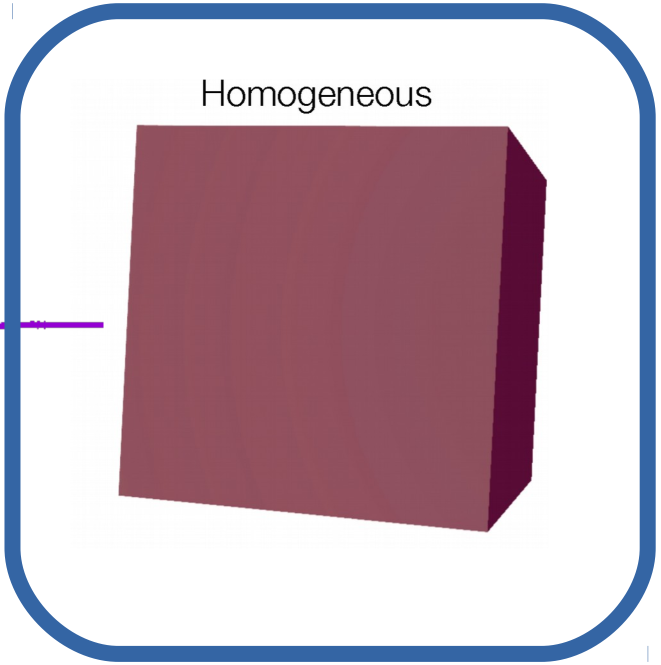


Near-critical plasma

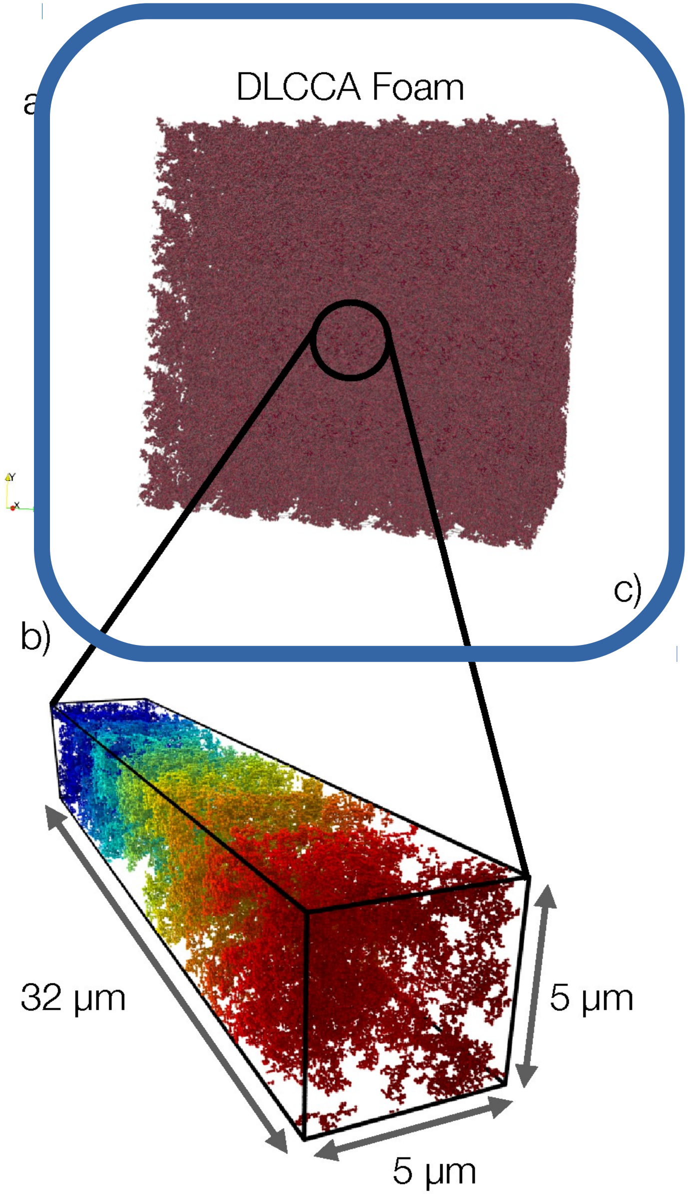
When I consider laser-interaction with a near-critical nanostructured target...

Laser



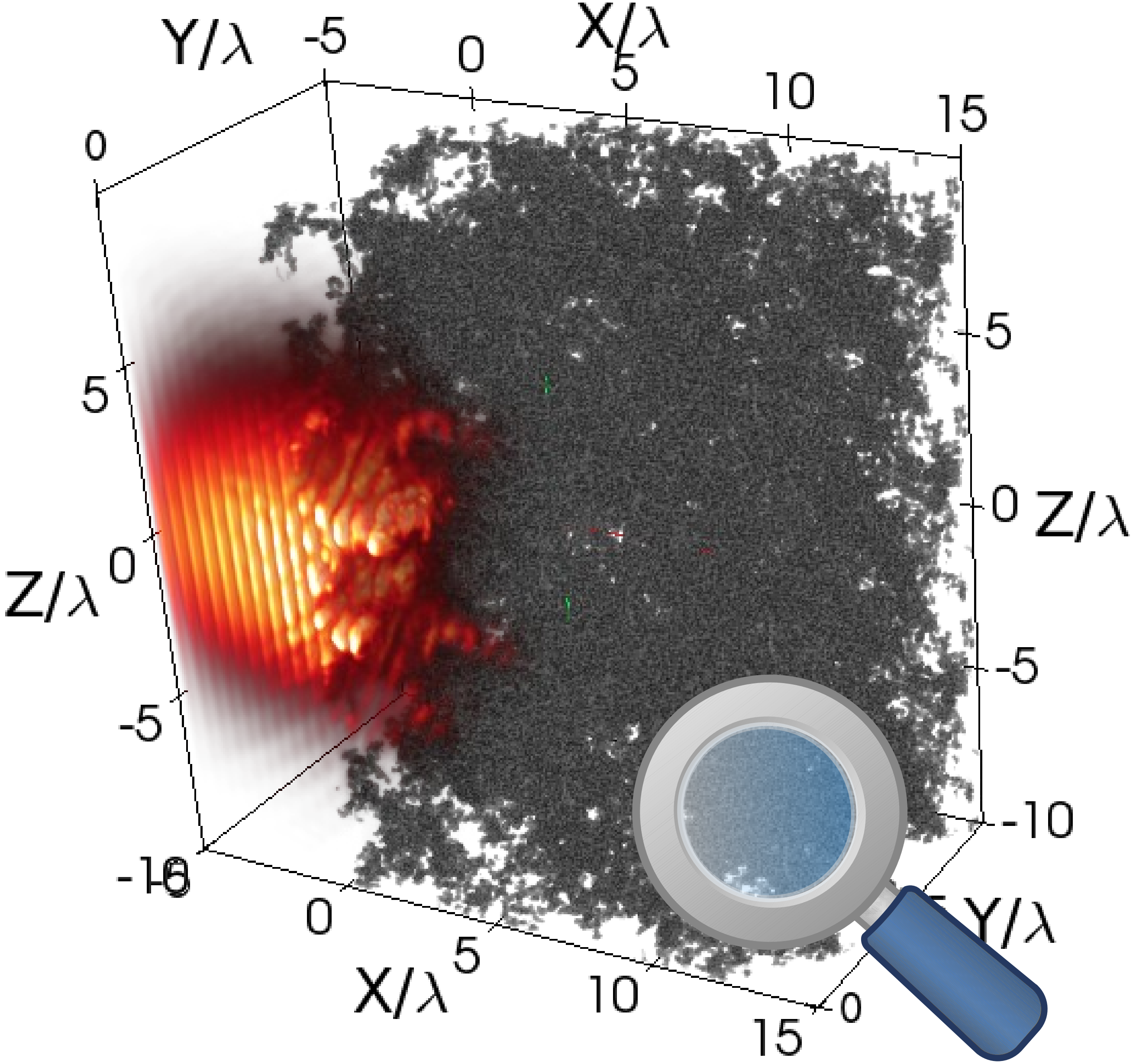


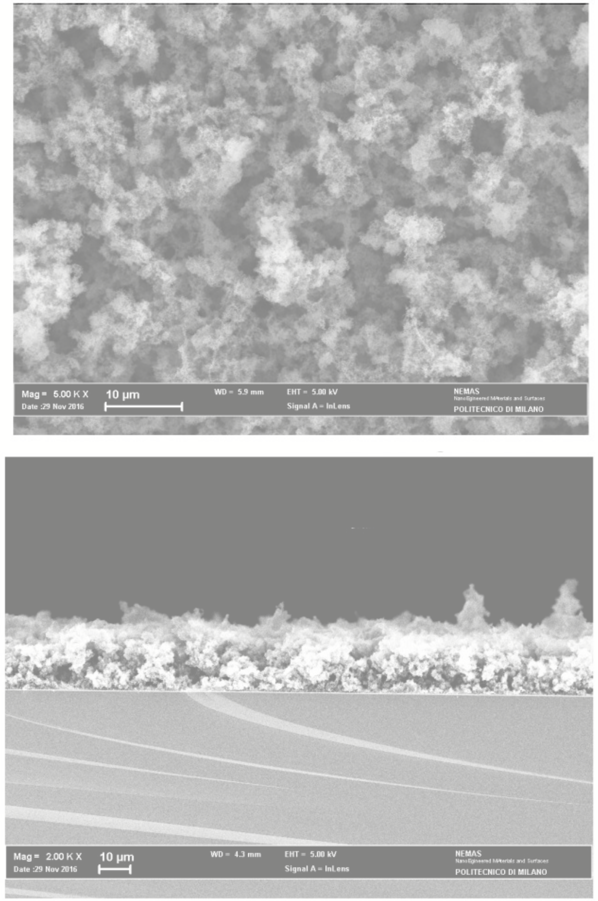
VS



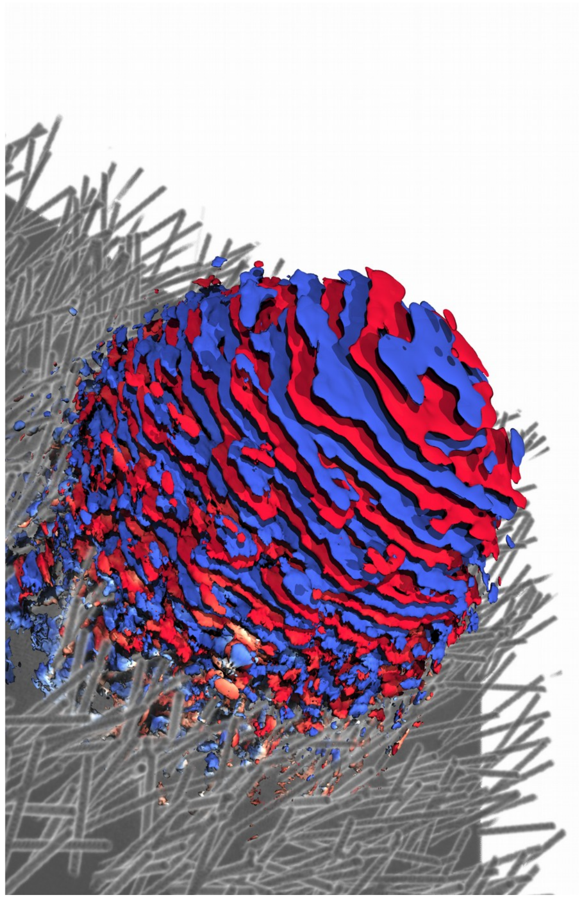
...should I consider the role of the nanostructure?

Particle-In-Cell (PIC) simulations could be very useful!

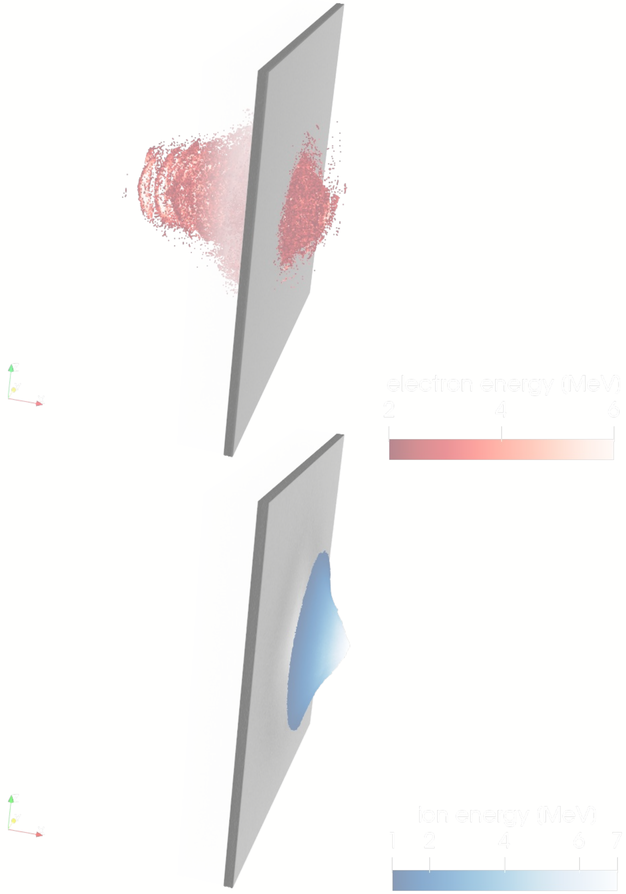




Nanostructured low-density materials



Modeling of laser interaction with nanostructures



Enhanced laser-driven ion acceleration

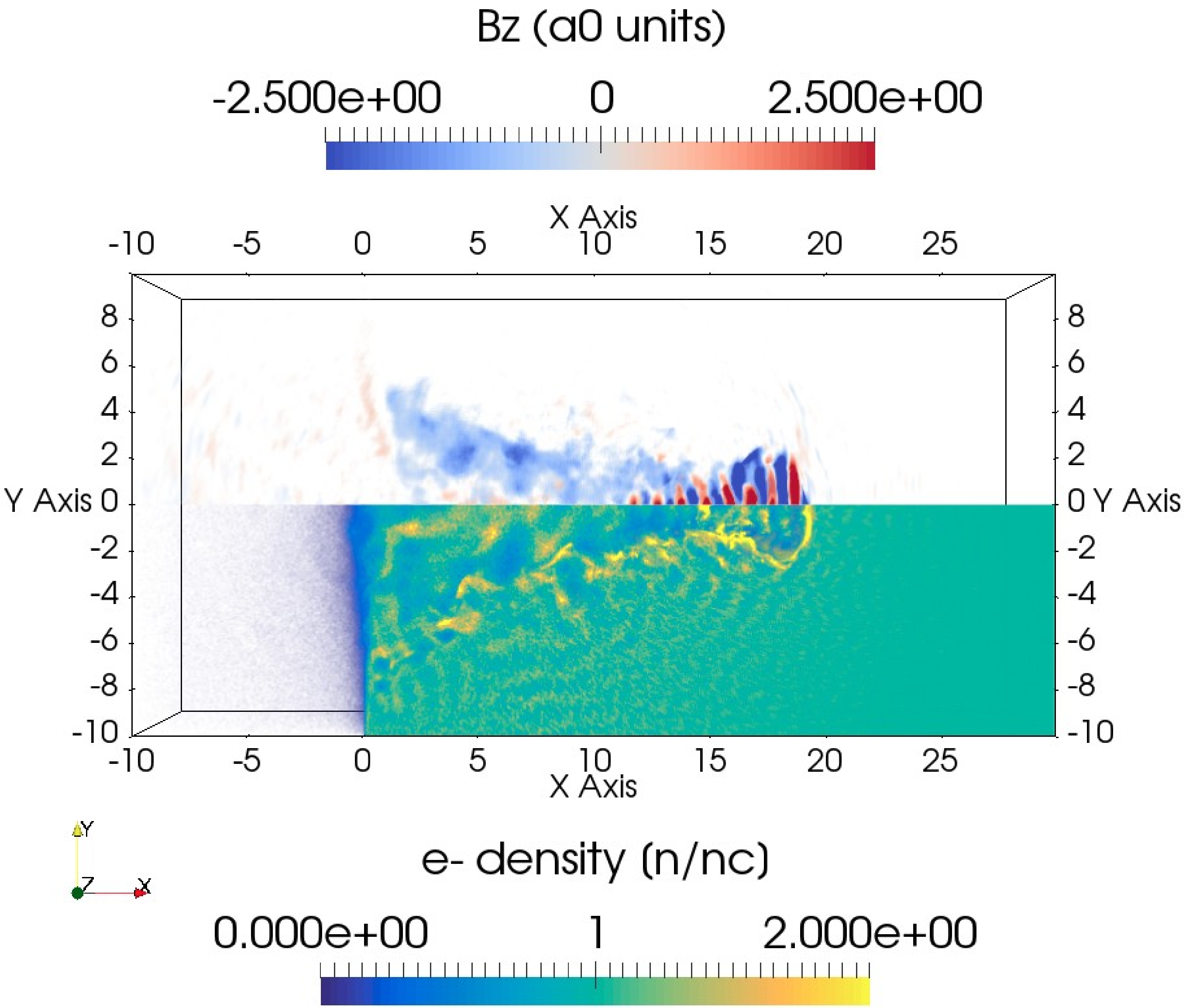
We simulated

$\langle n_e \rangle \sim 3\, n_c$

$a_0 = 5, 15, 45$

30 fs FWHM pulse

(no pre-pulse,
pre-ionized plasma)



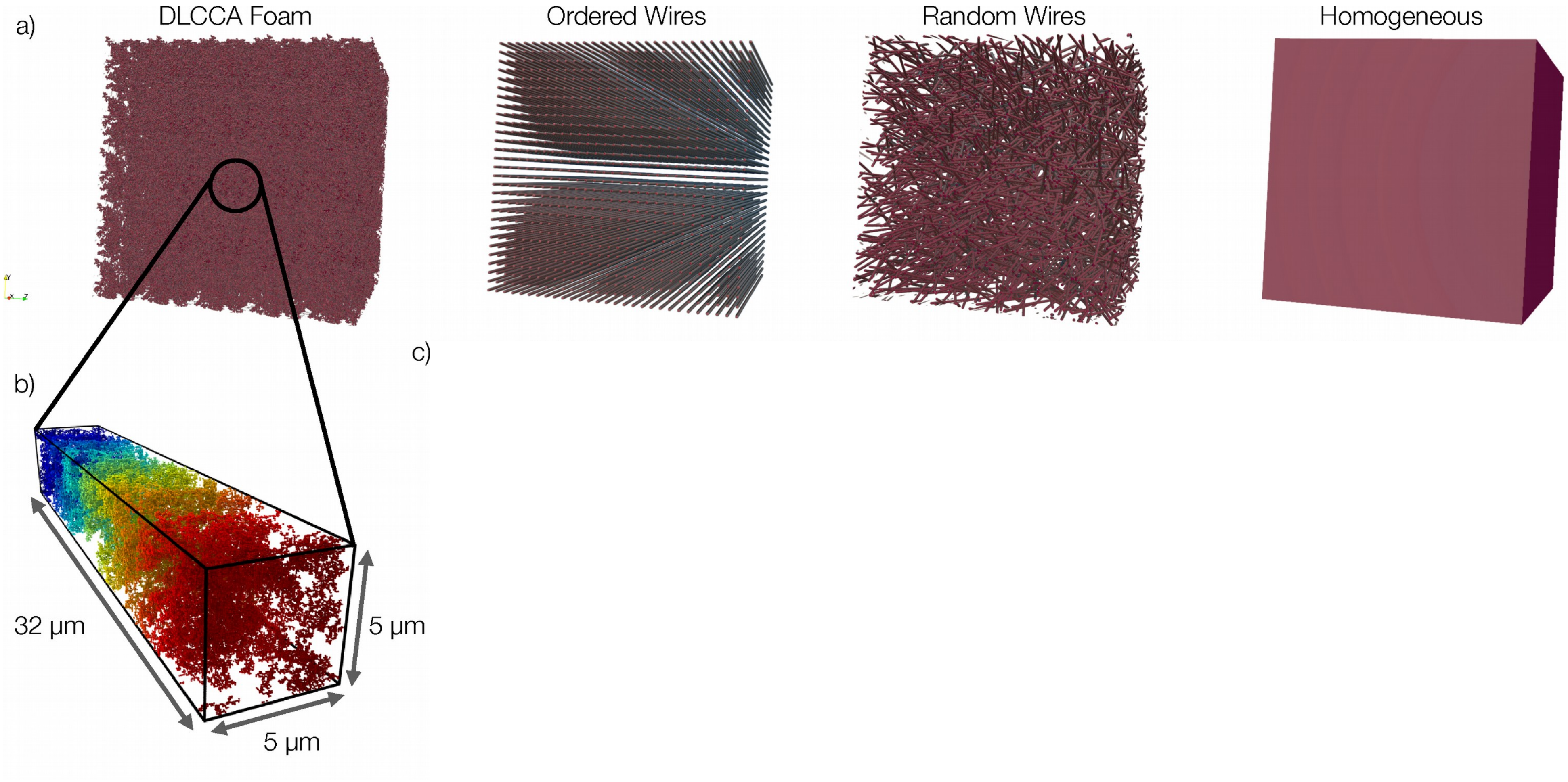
piccante
Open Source PIC Code

CINECA

We performed an extensive study of laser-interaction with these plasmas

L.Fedeli et al. Sci. Rep. 8 3834 (2018)

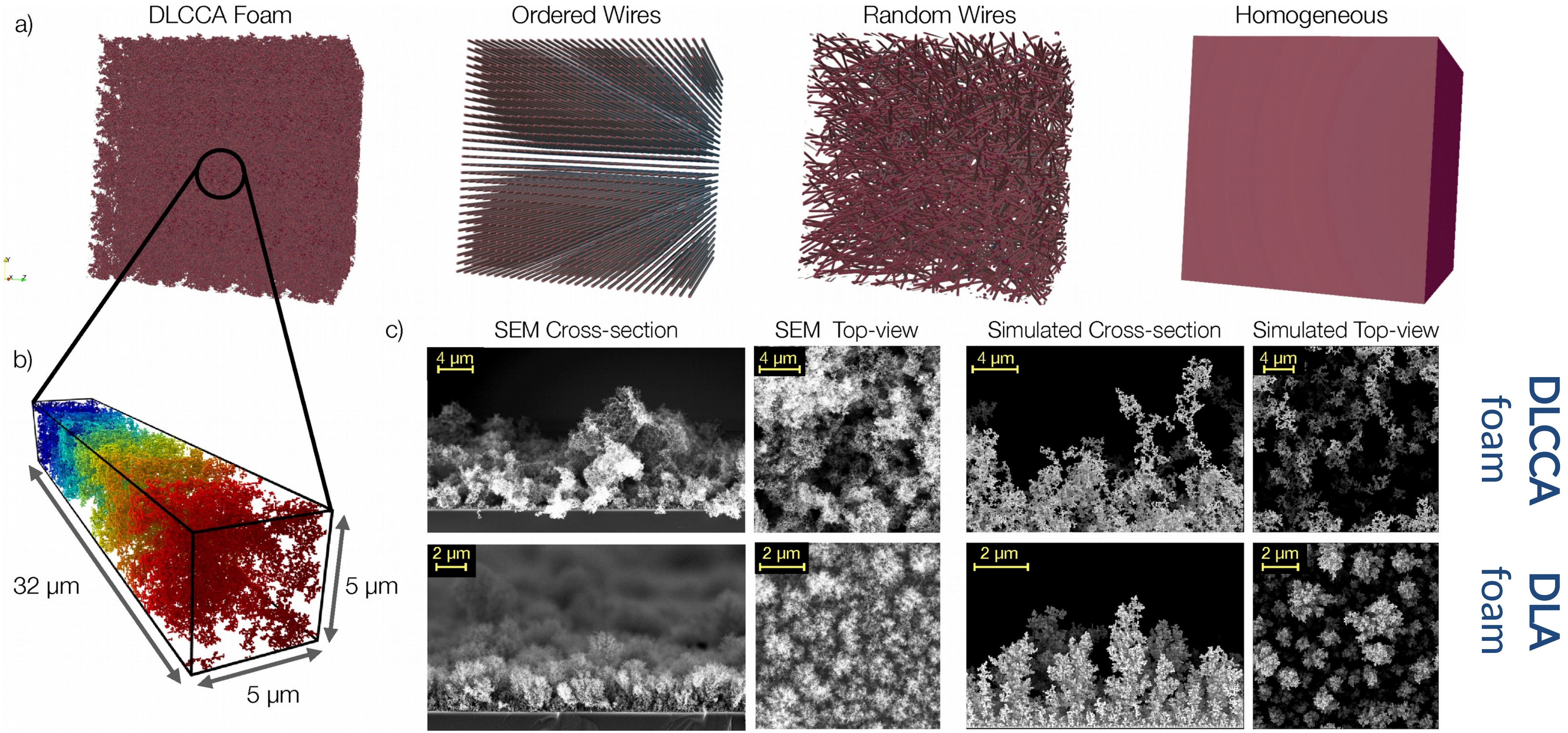
L.Fedeli et al. Eur.Phys.J. D, 71: 202 (2017)



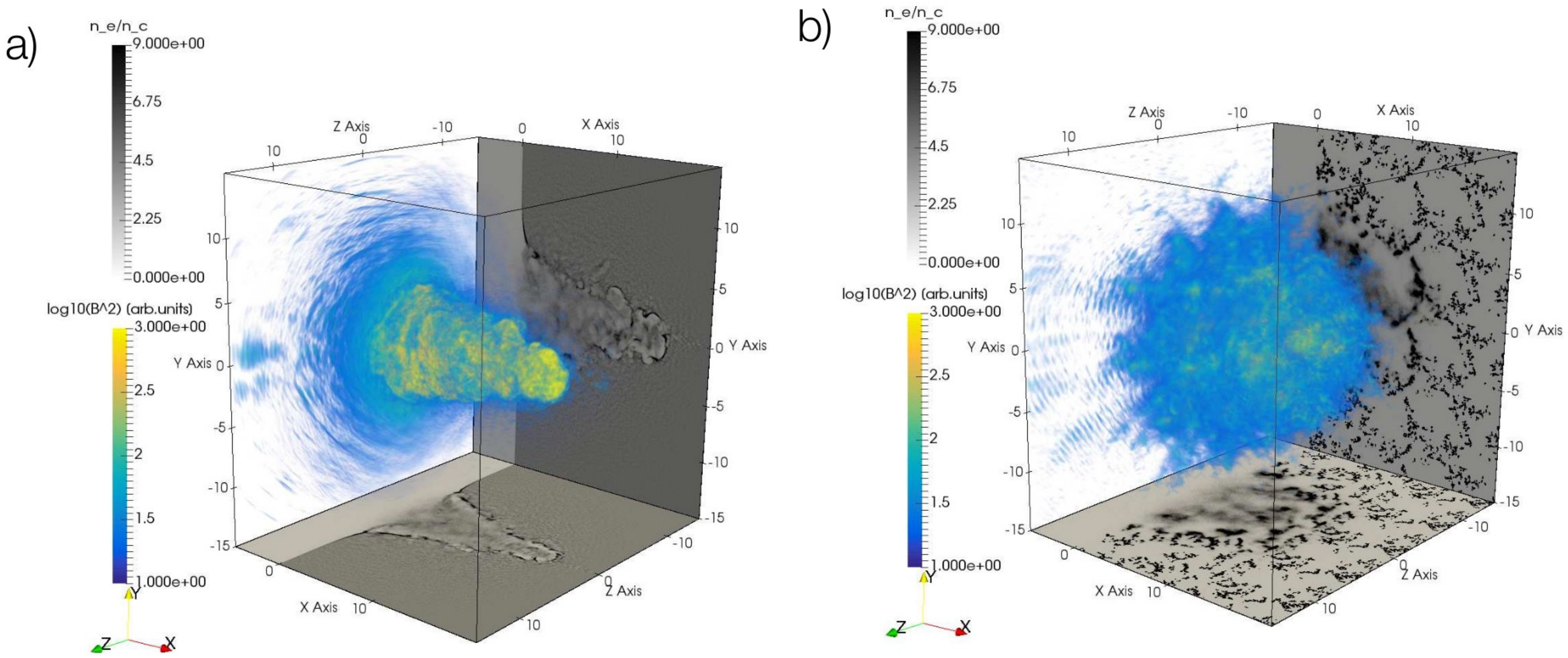
We even tested 2 different foam morphologies

L.Fedeli et al. Sci. Rep. 8 3834 (2018)

L.Fedeli et al. Eur.Phys.J. D, 71: 202 (2017)



There are differences in pulse propagation

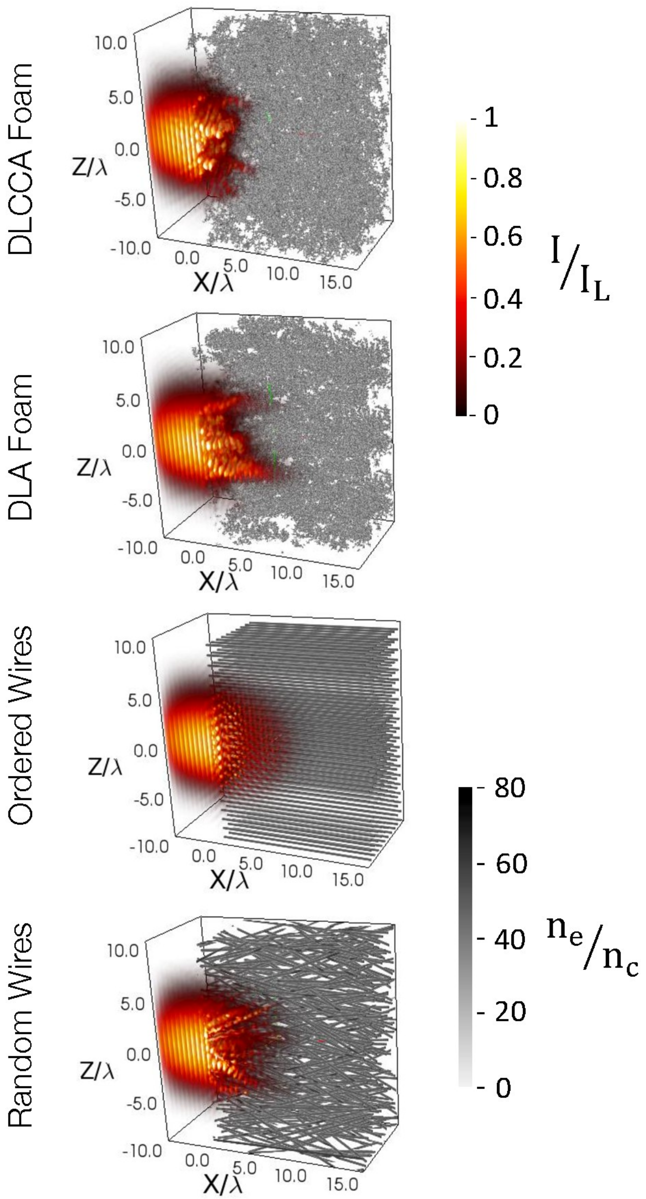


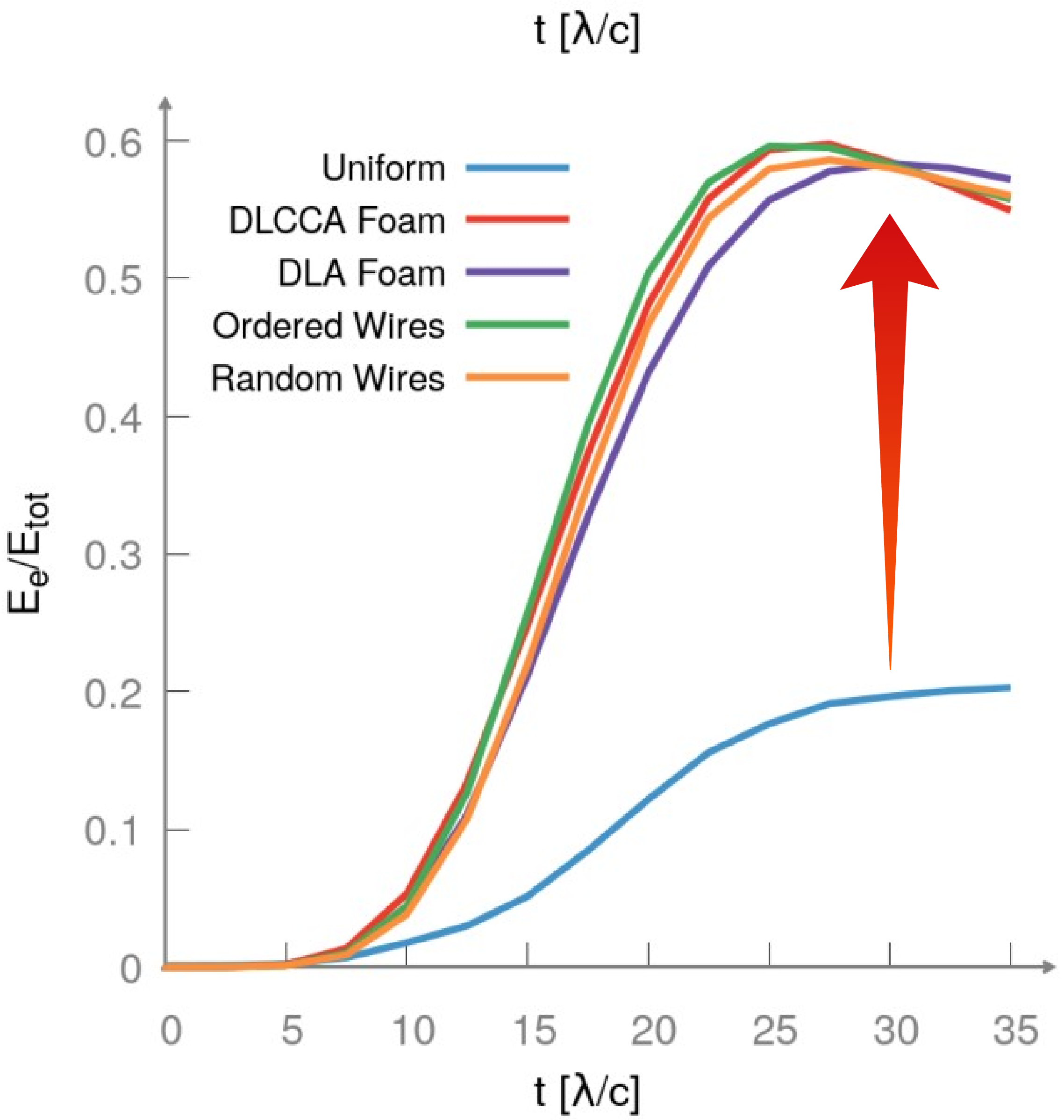
$a_0 = 15, \langle n_e \rangle = 3\, n_c$

Laser $a_0 = 5$

$<n_e> = 3 n_c$

structures lead to higher absorption

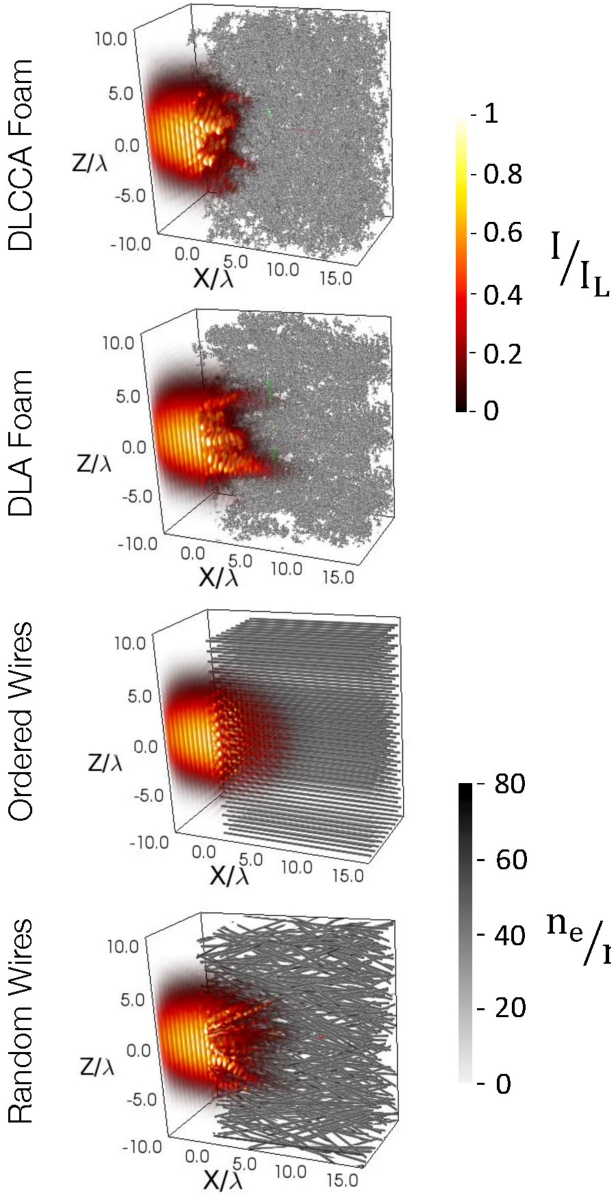


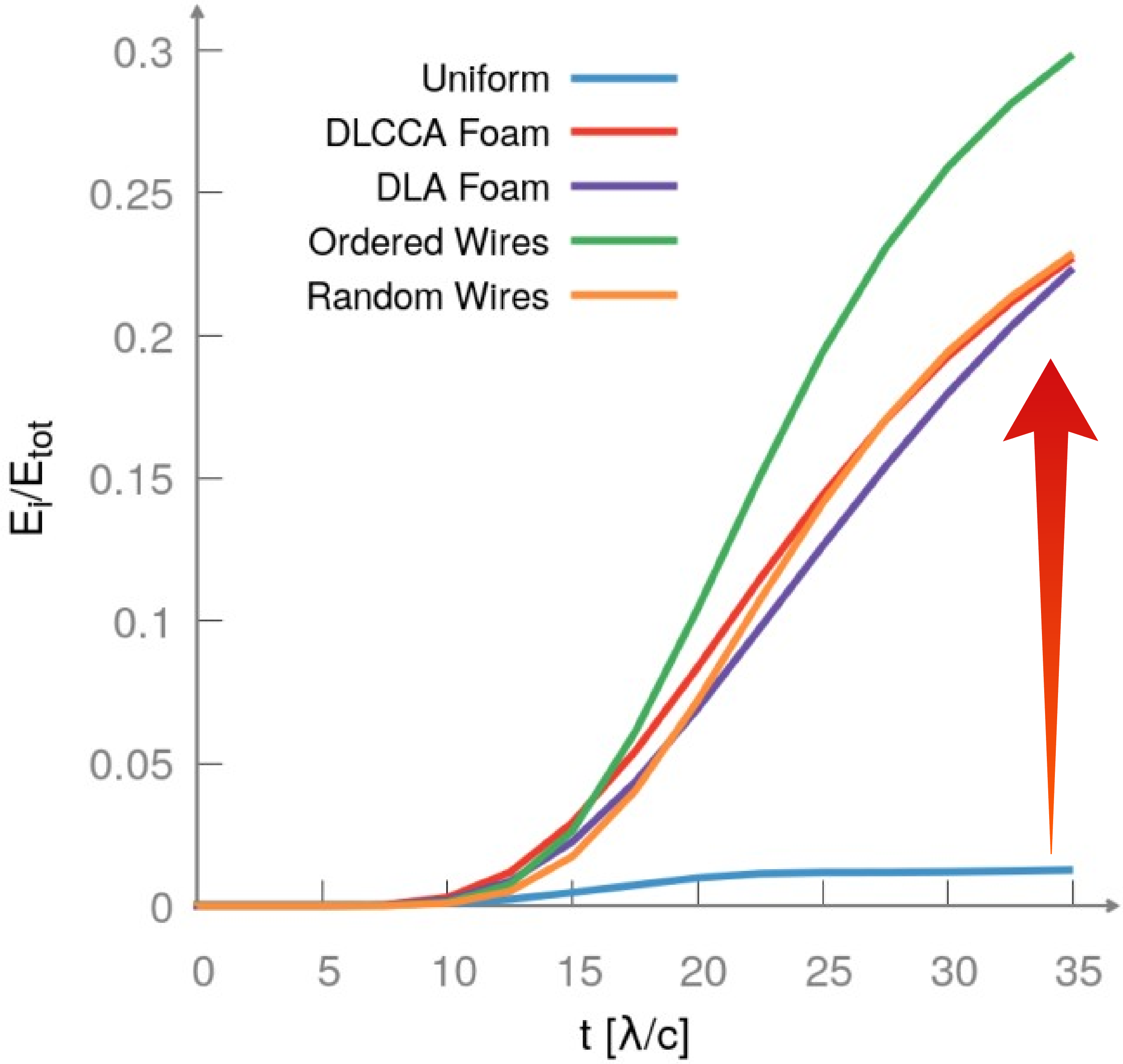


Laser $a_0 = 5$

$\langle n_e \rangle = 3\, n_c$

Higher absorption efficiency into **Ion kinetic energy**



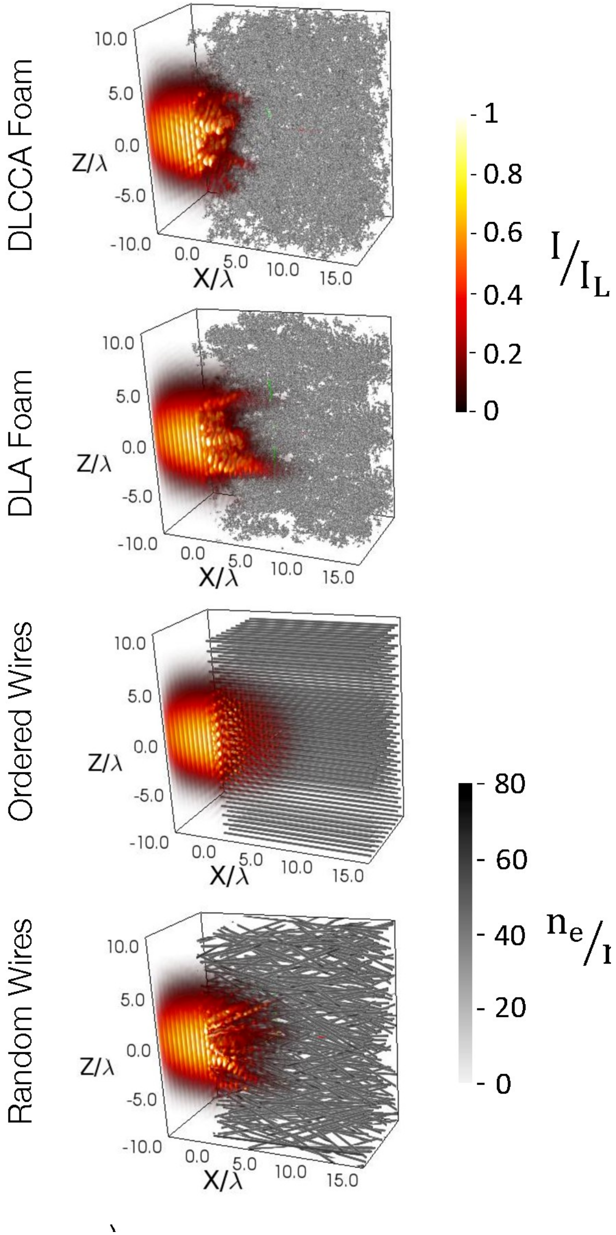


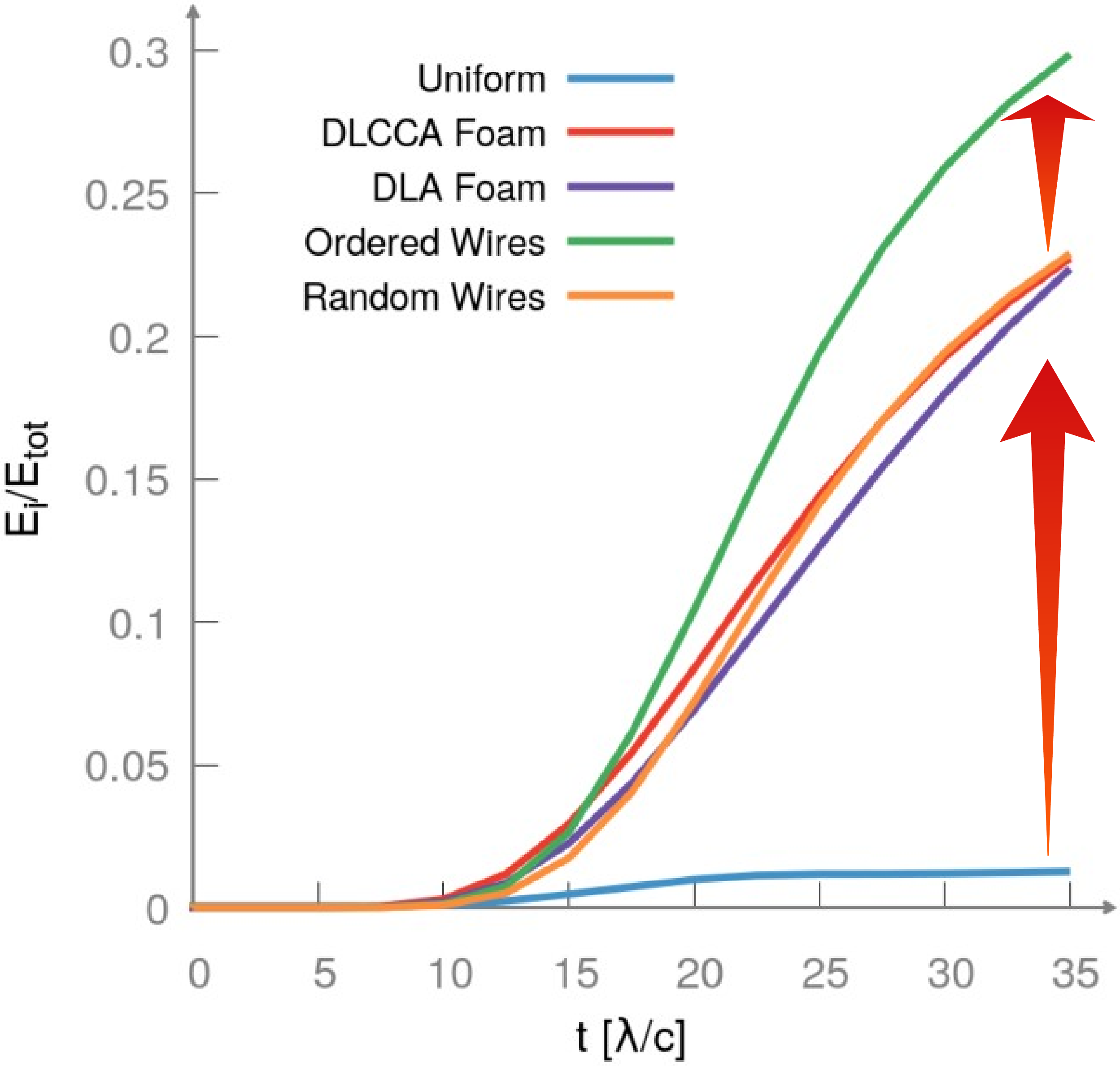
Laser $a_0 = 5$

$<n_e> = 3\ n_c$

Higher absorption efficiency into

Ion kinetic energy

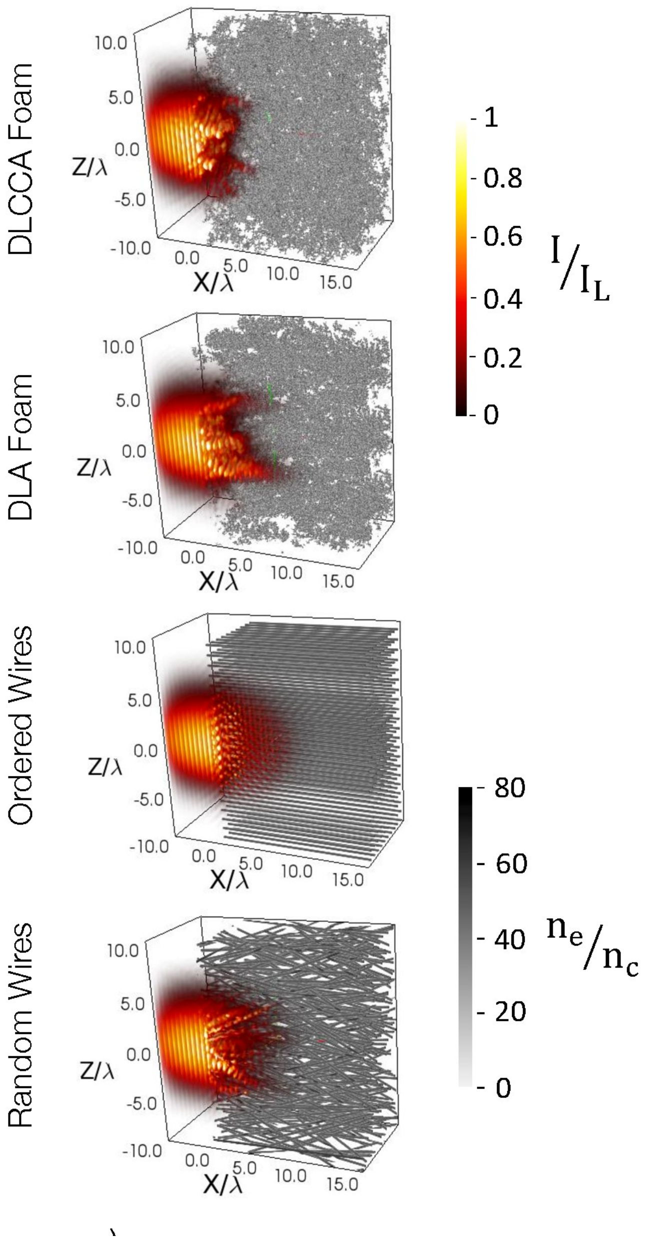


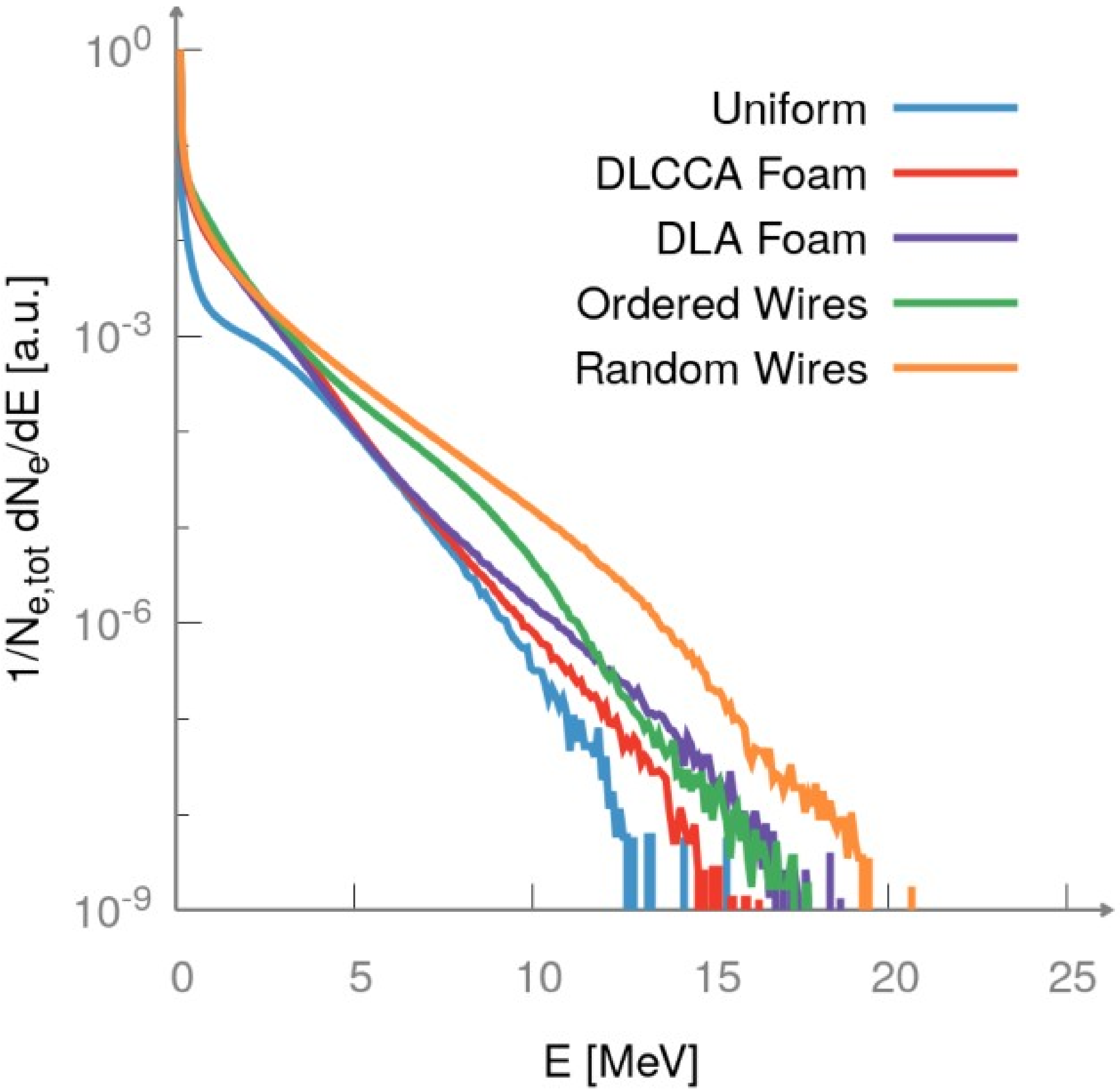


Laser $a_0 = 5$

$<n_e> = 3\,n_c$

Different structures lead to significant differences in the **electron spectra**

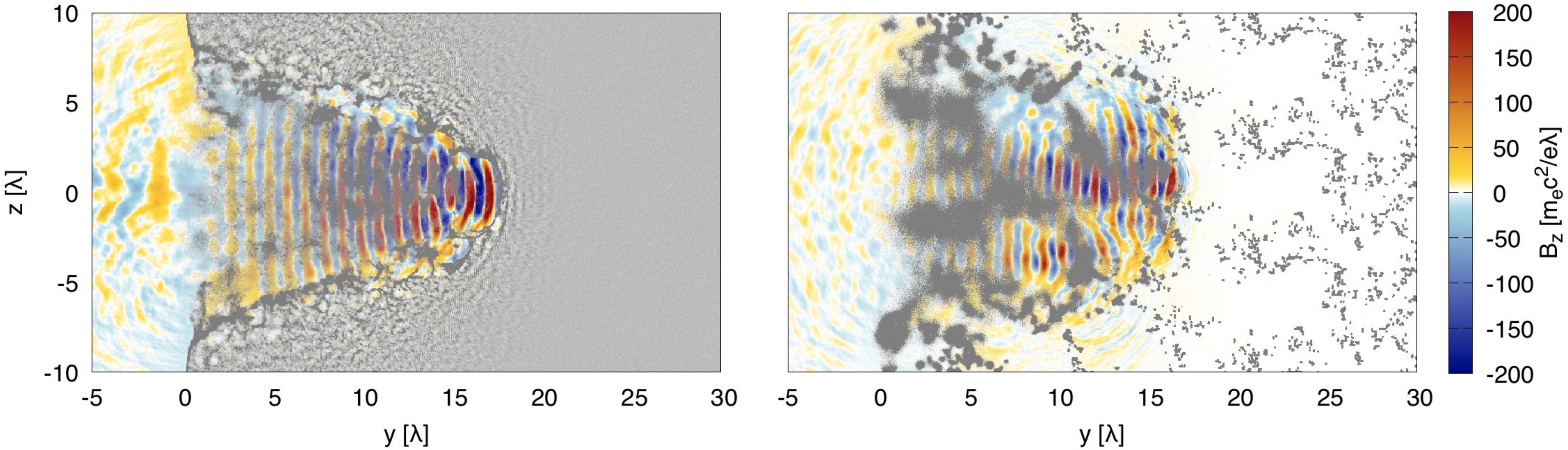




Laser $\mathbf{a_0 = 45}$

$<n_e> = 3\ n_c$

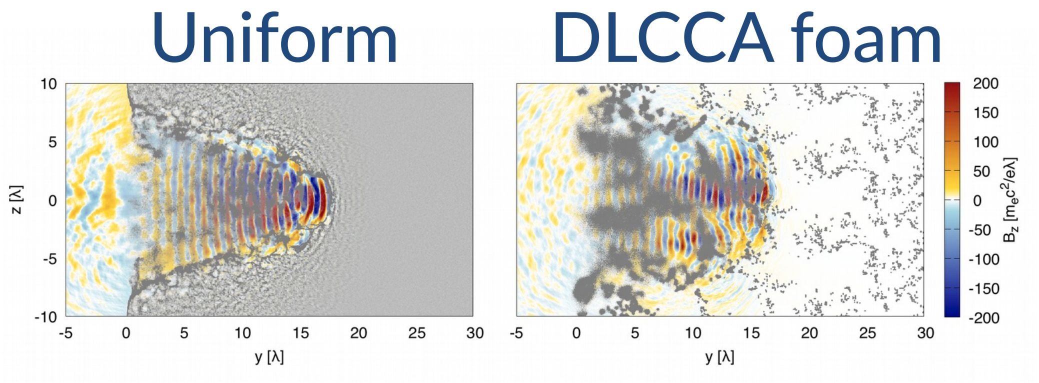
This scenario is suitable for electron acceleration in the plasma channel

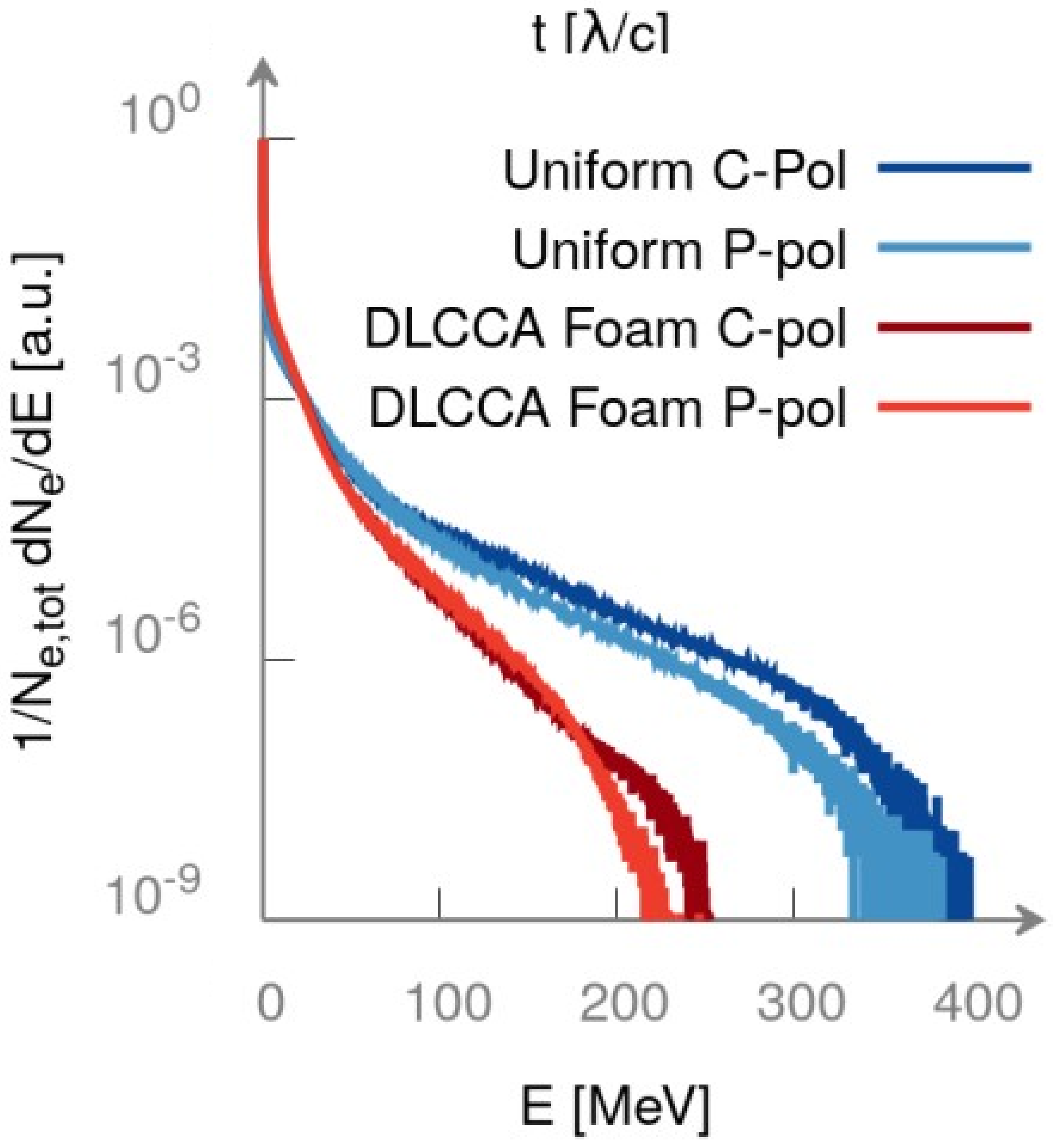


Laser a_0 = 45 (C-pol & P-pol)

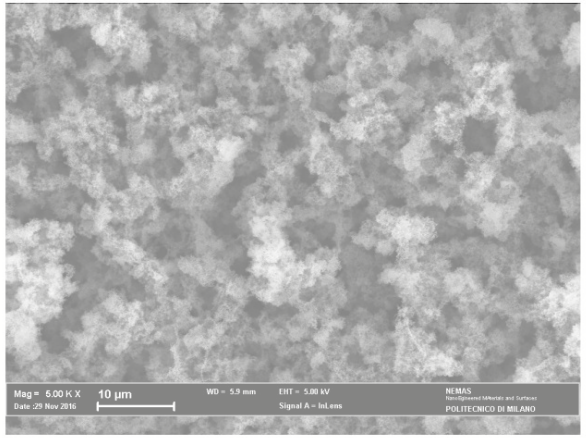
$<n_e> = 3\ n_c$

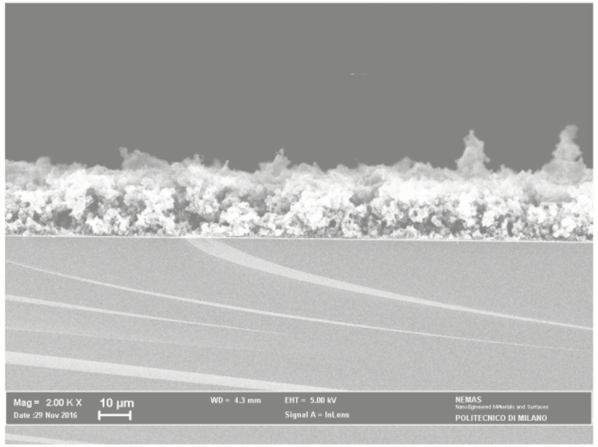
Nanostructure Lowers the temperature of electron energy spectra



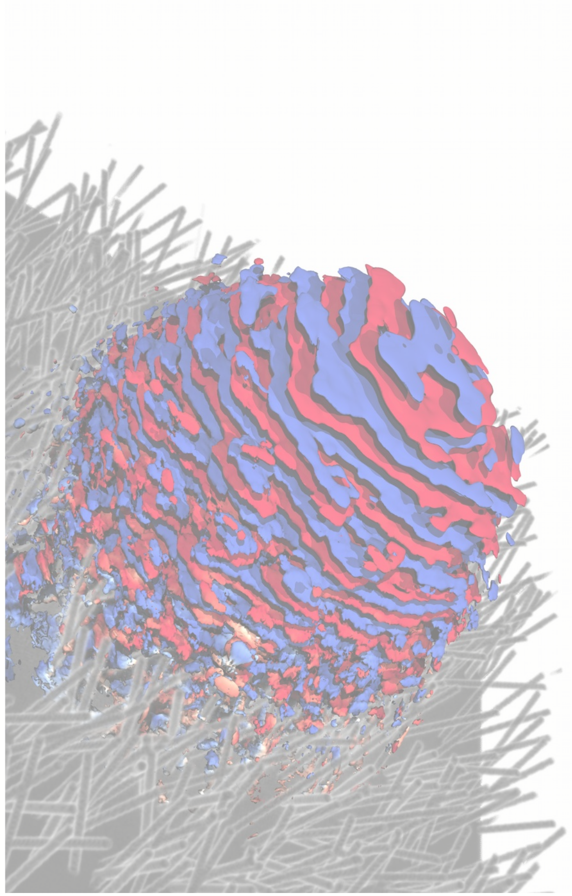


Provided that the pulse contrast is sufficiently high, **the nanostructure seems to play a role**

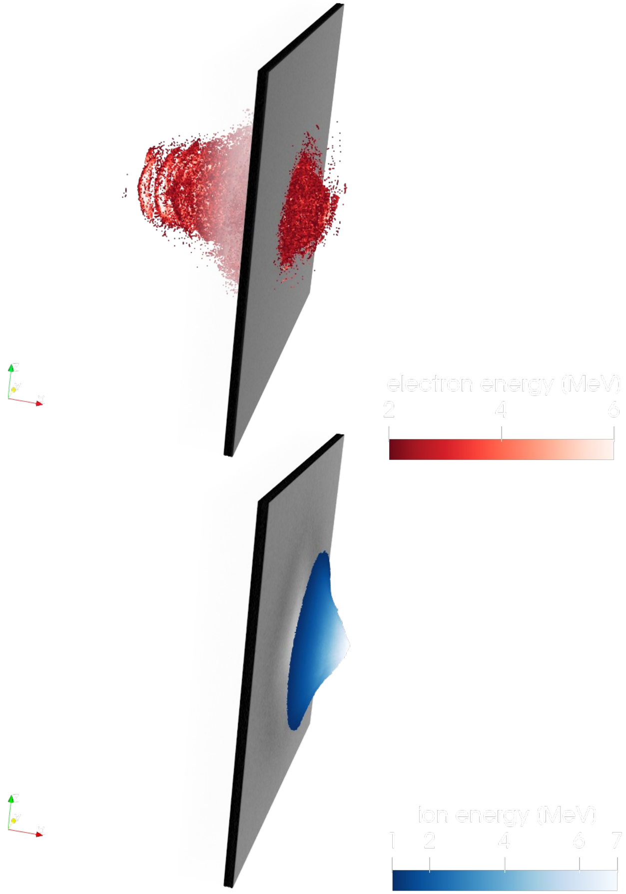




Nanostructured low-density materials

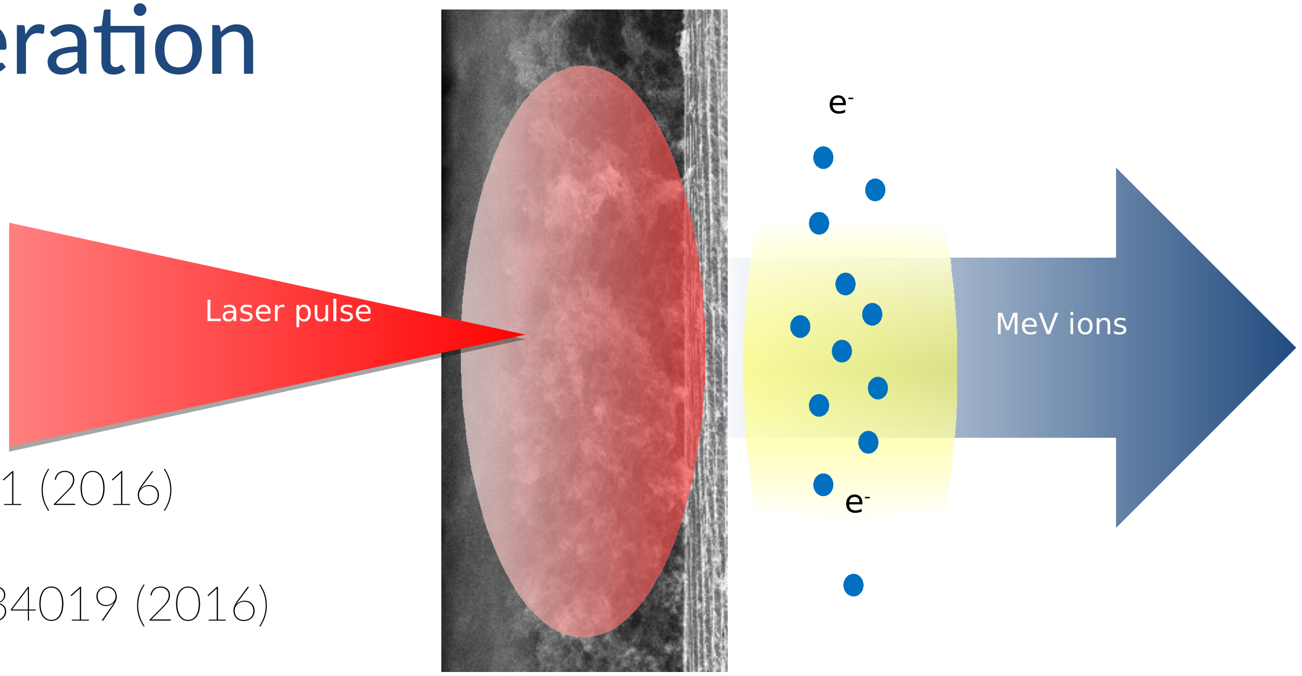


Modeling of laser interaction with nanostructures



Enhanced laser-driven ion acceleration

Double-layer targets are a promising target concept for laser-driven ion acceleration



M.Passoni et al Phys. Rev. Accel. Beams 19, 061301 (2016)

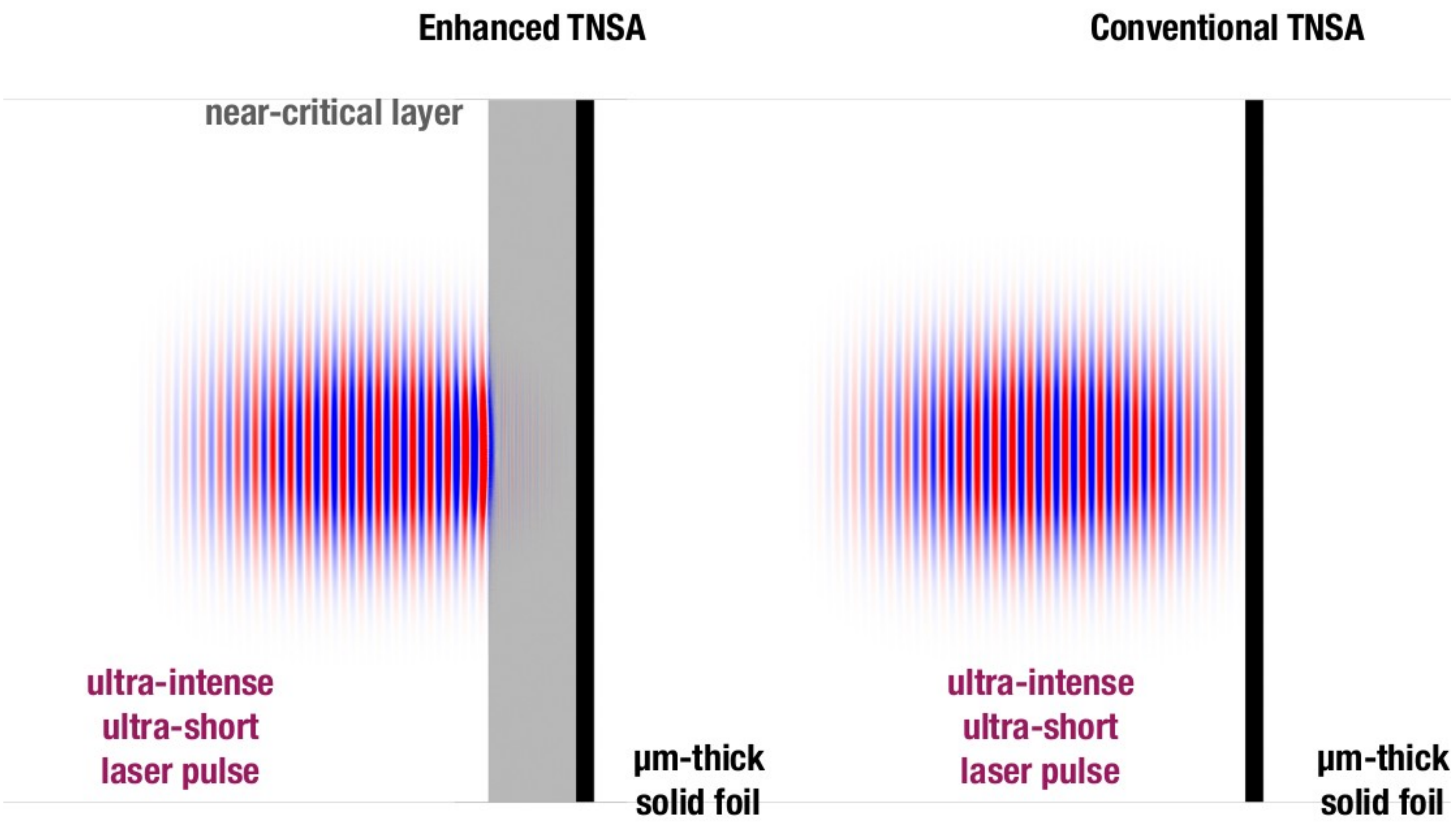
I. Prencipe et al Plasma Phys. Control. Fusion 58 034019 (2016)

M Passoni et al 2014 Plasma Phys. Control. Fusion 56 045001 (2014)

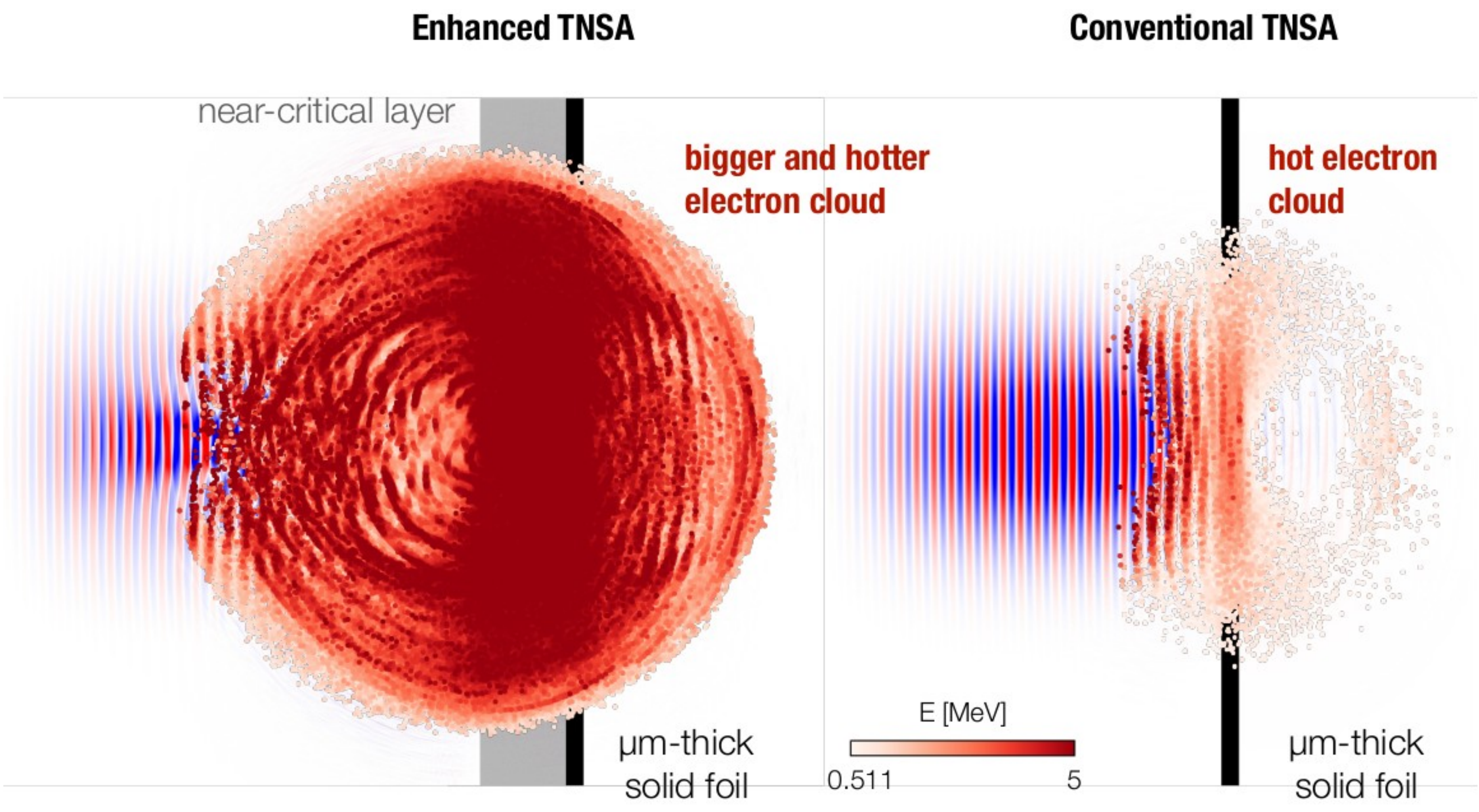
A. Sgattoni et al Phys. Rev. E 85, 036405 (2012)

J.H. Bin et al Phys. Rev. Lett. 120, 074801 (2018)

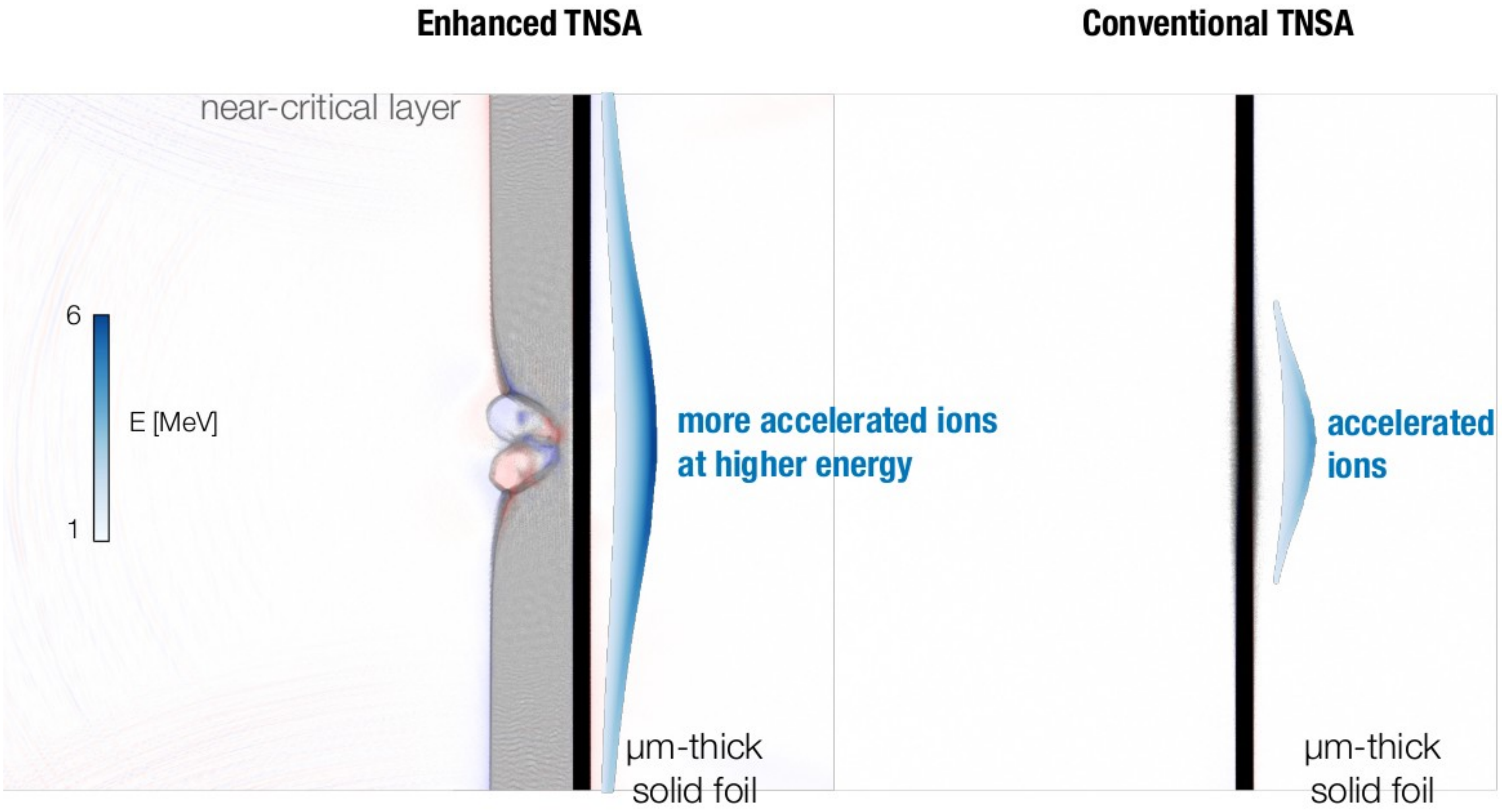
This is due to the higher absorption efficiency



This is due to the higher absorption efficiency



This is due to the higher absorption efficiency

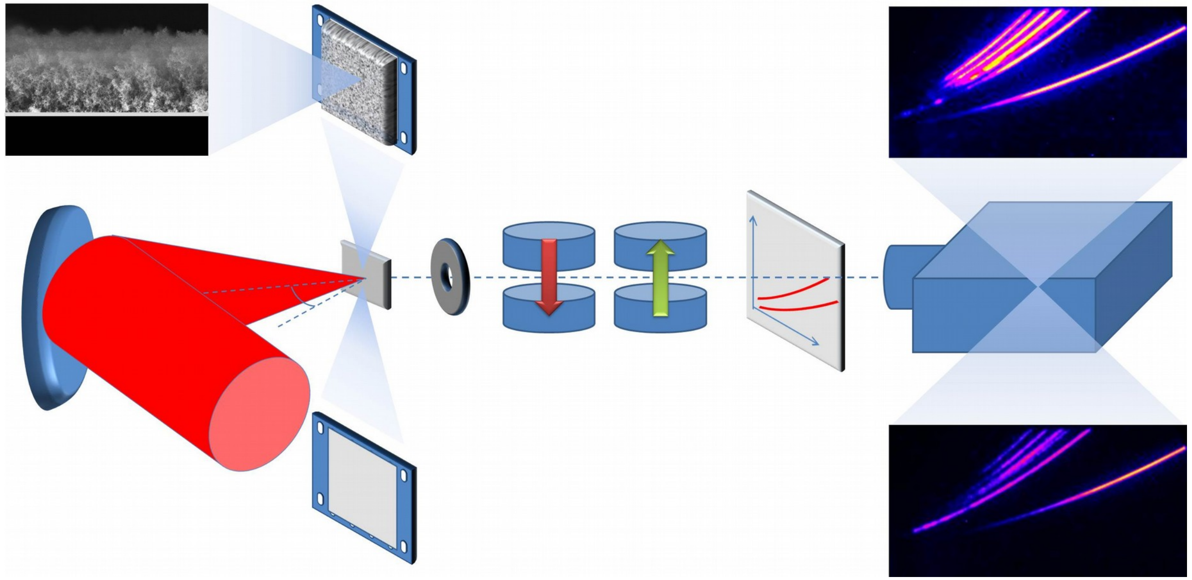


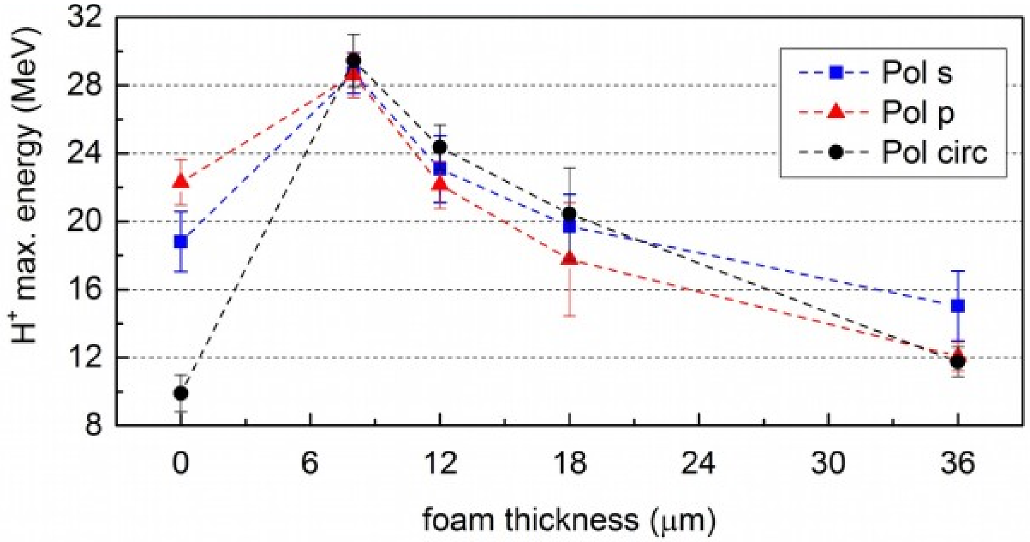
Double-layer targets are a promising target concept for laser-driven ion acceleration

2014/2015

PULSER laser

7.4J, 30 fs, ≈5x**10^{20} W/cm^2**

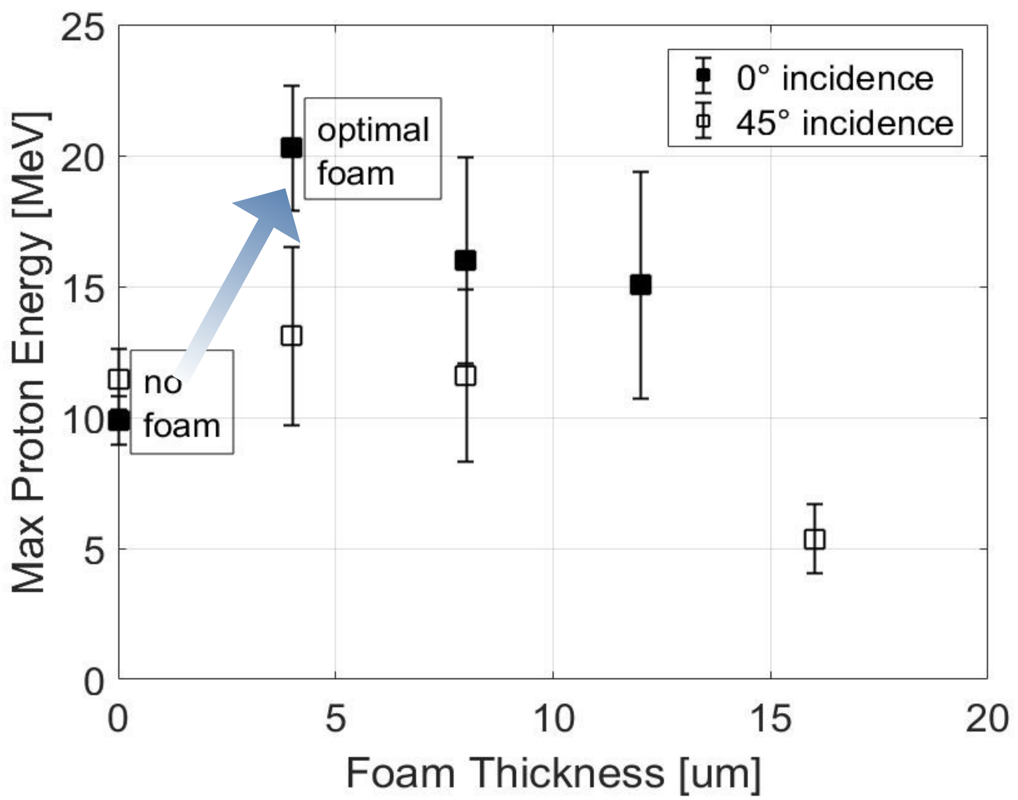




Double-layer targets are a promising target concept for laser-driven ion acceleration

HZDR

2017
DRACO laser
1J, 30 fs, ≈**10^{20} W/cm^2**

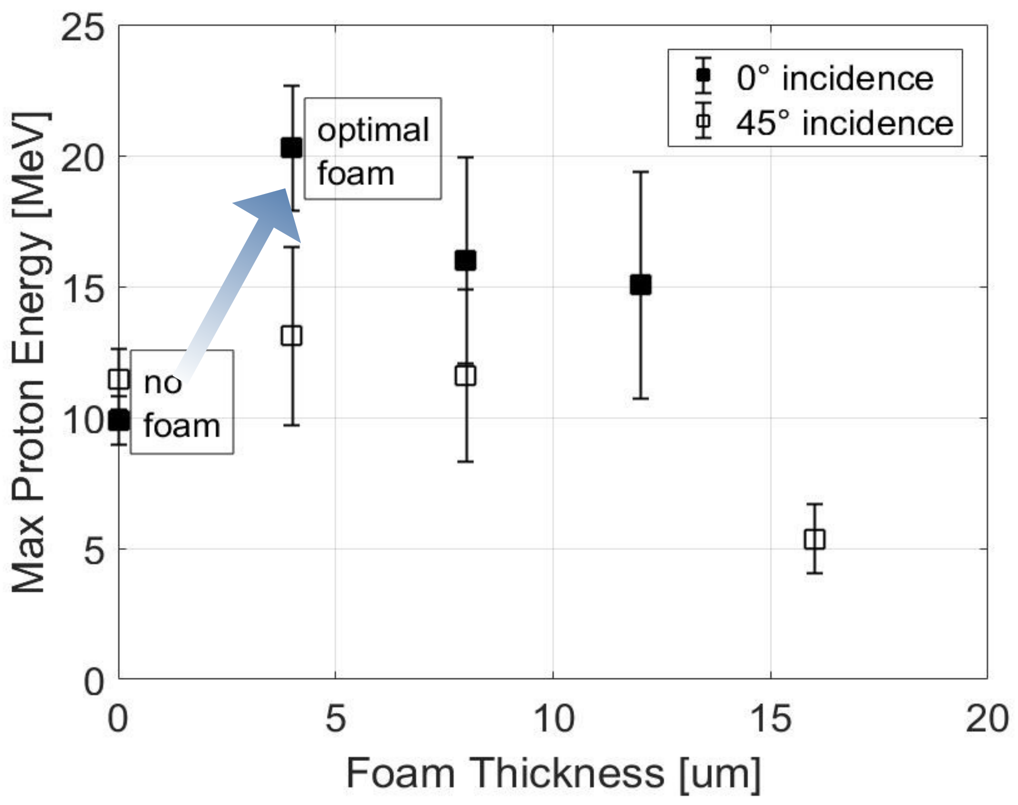


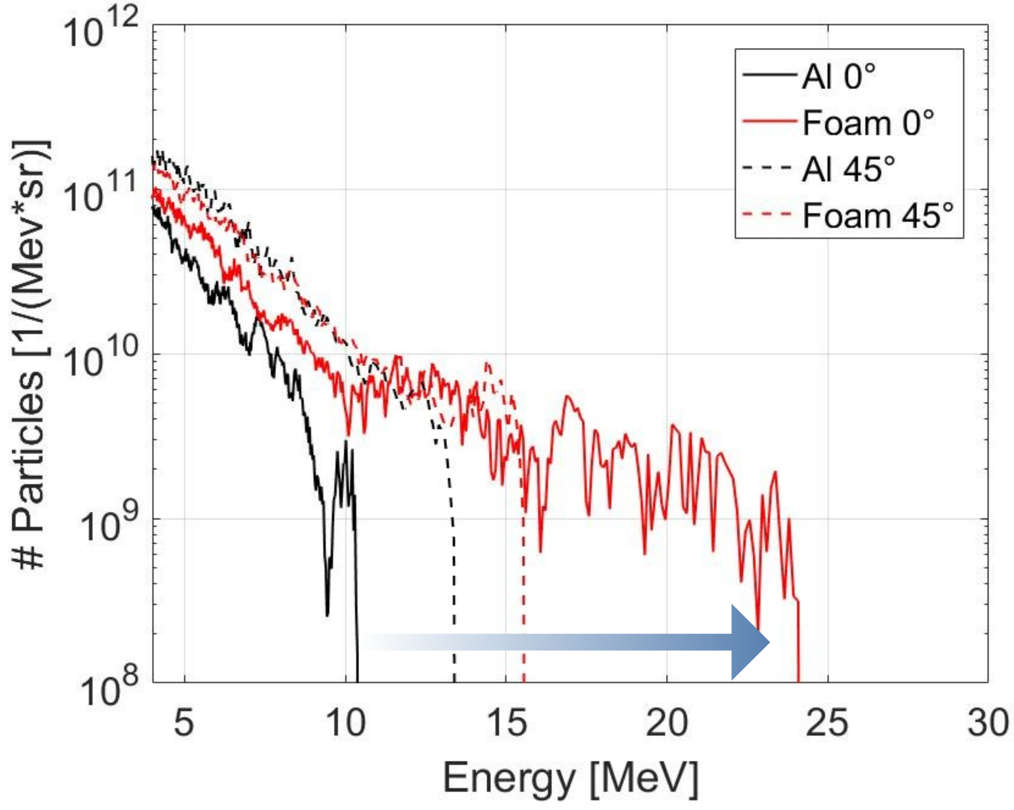
Double-layer targets are a promising target concept for laser-driven ion acceleration

2017

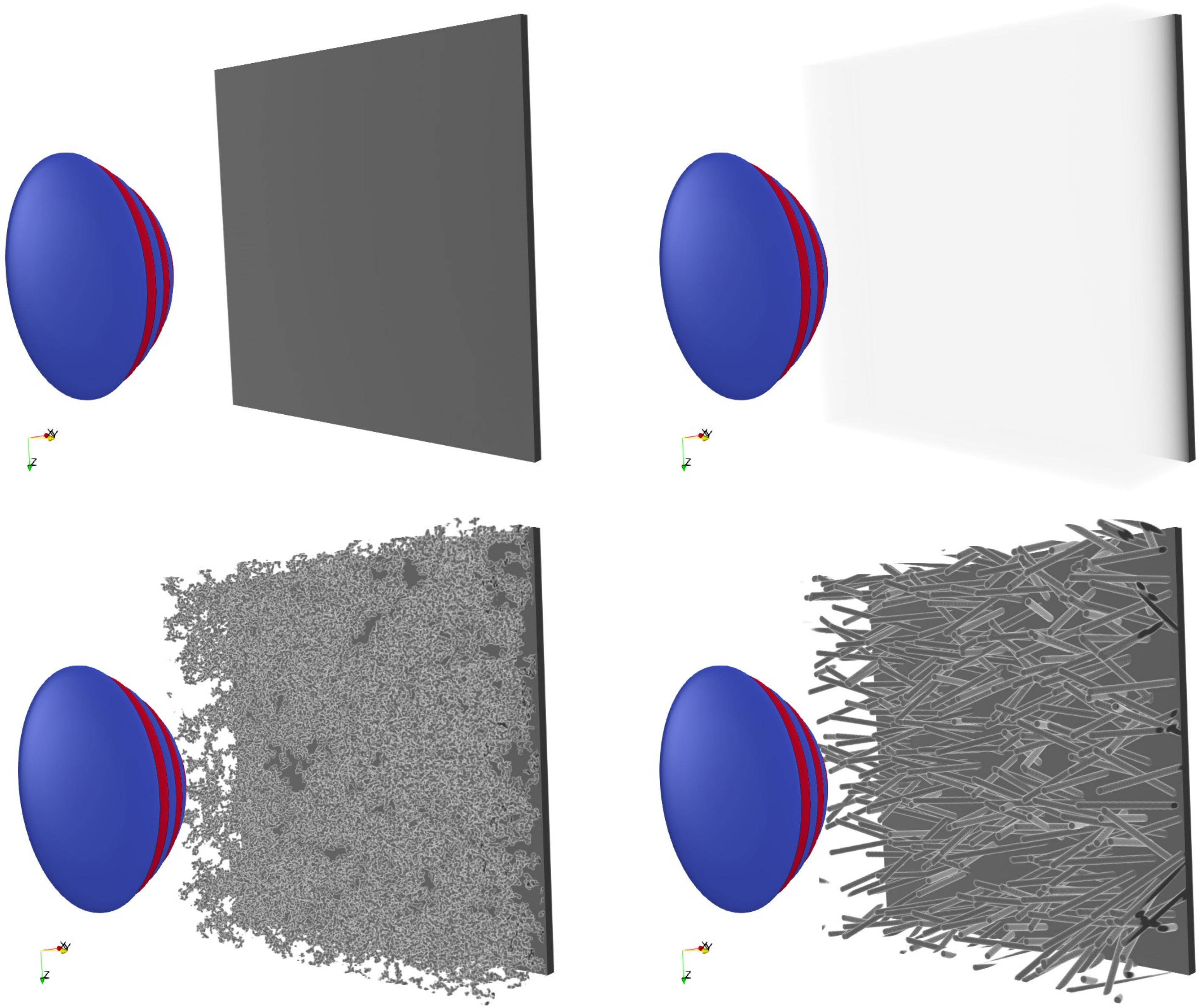
DRACO laser

1J, 30 fs, ≈10^{20} W/cm^2

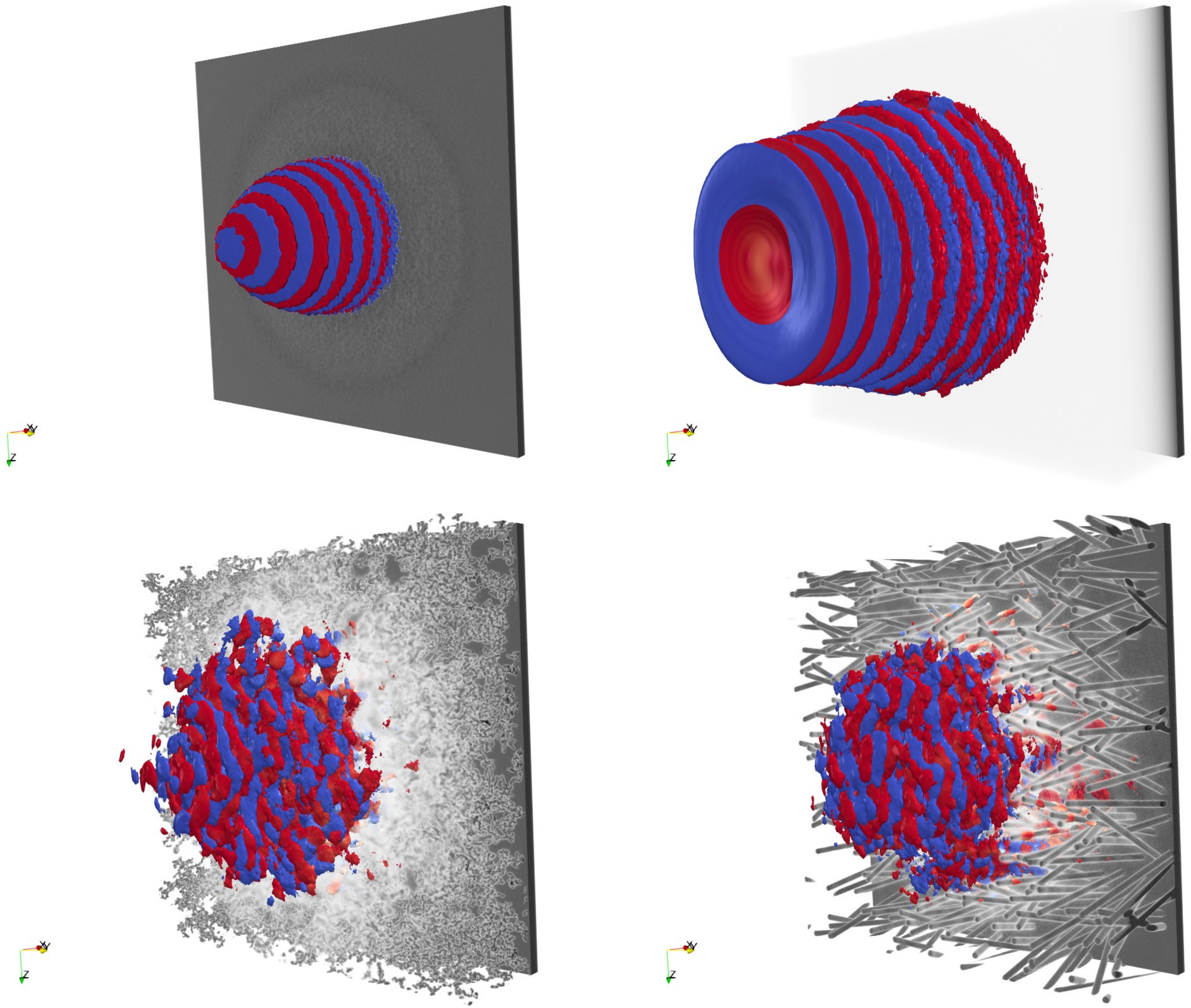




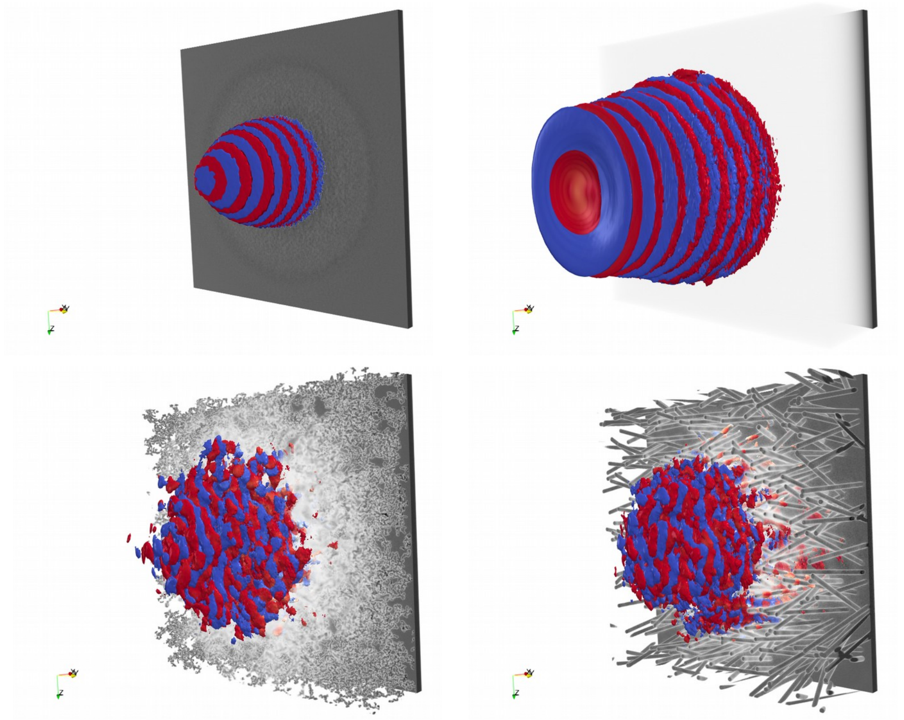
We are interested in double-layer targets irradiated at (relatively) low laser intensities (a0 ~ 4)

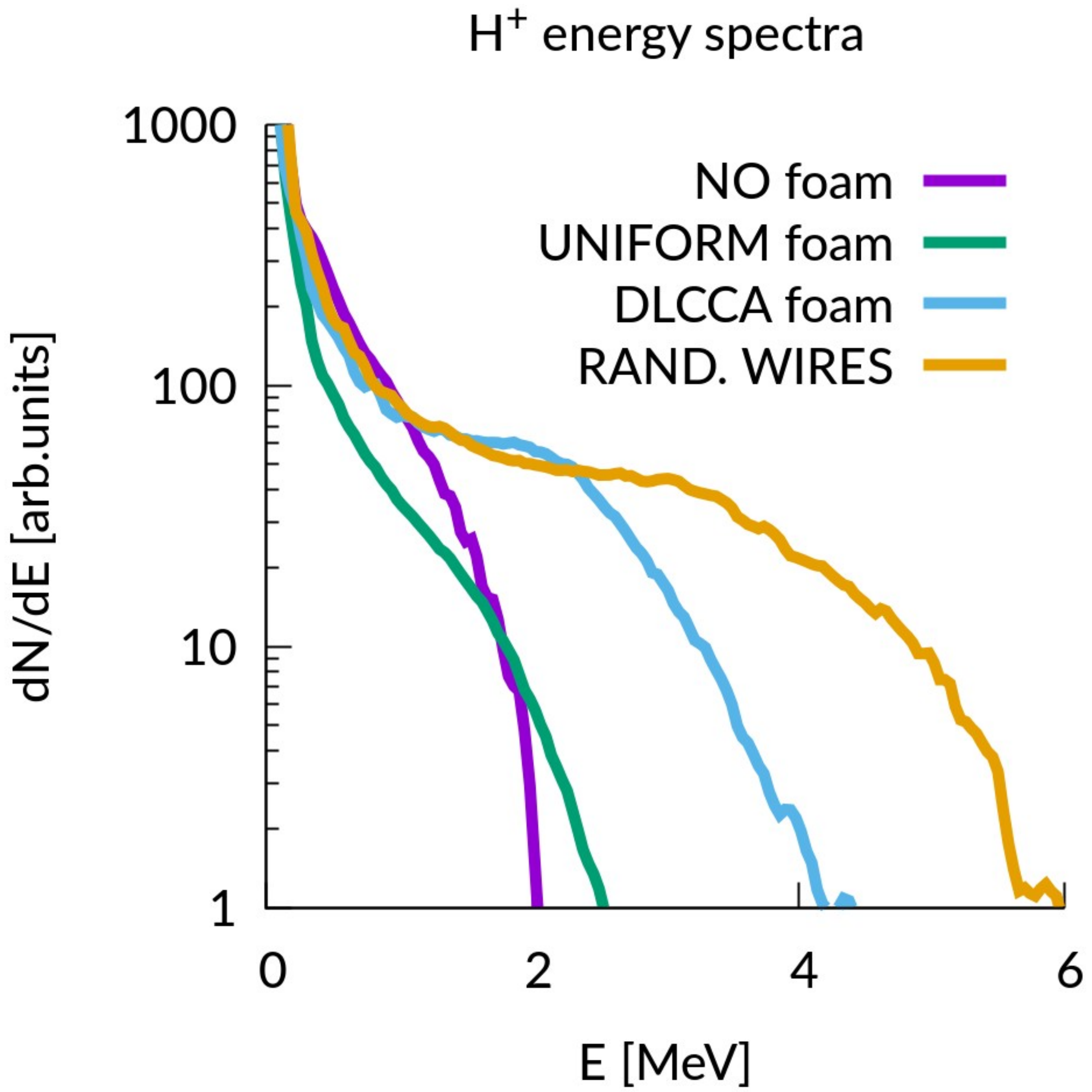


We are interested in double-layer targets irradiated at (relatively) low laser intensities (a0 ~ 4)

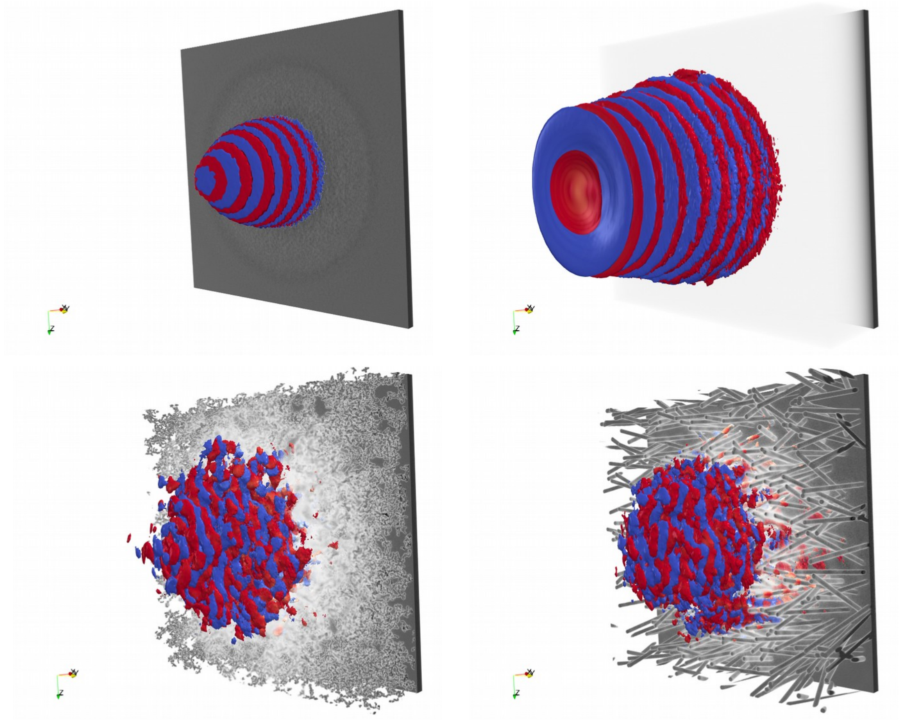


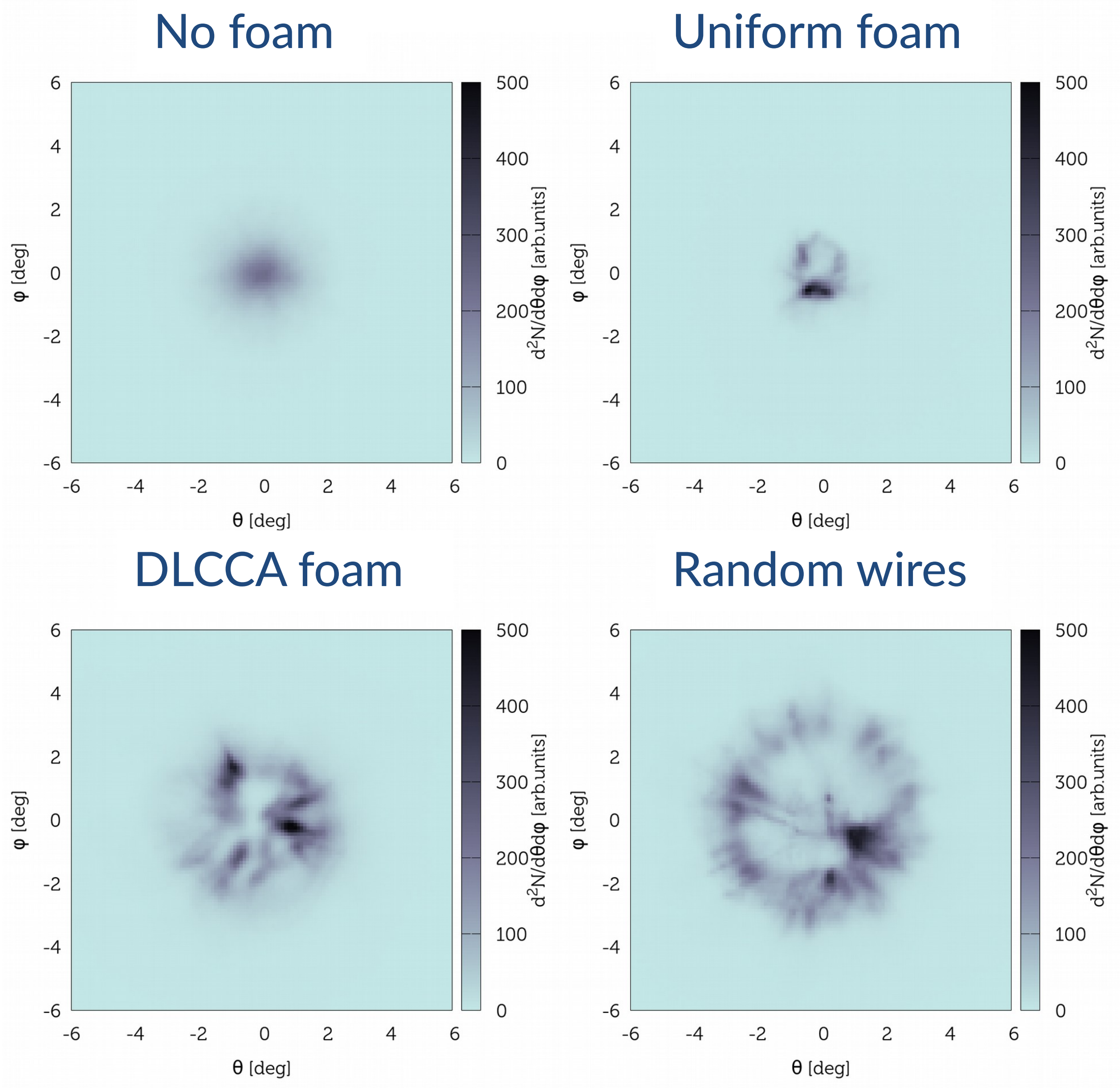
Nanostructures influence Ion energy spectra





Nanostructures influence Ion angular distribution (H^+ with E > 1 MeV)



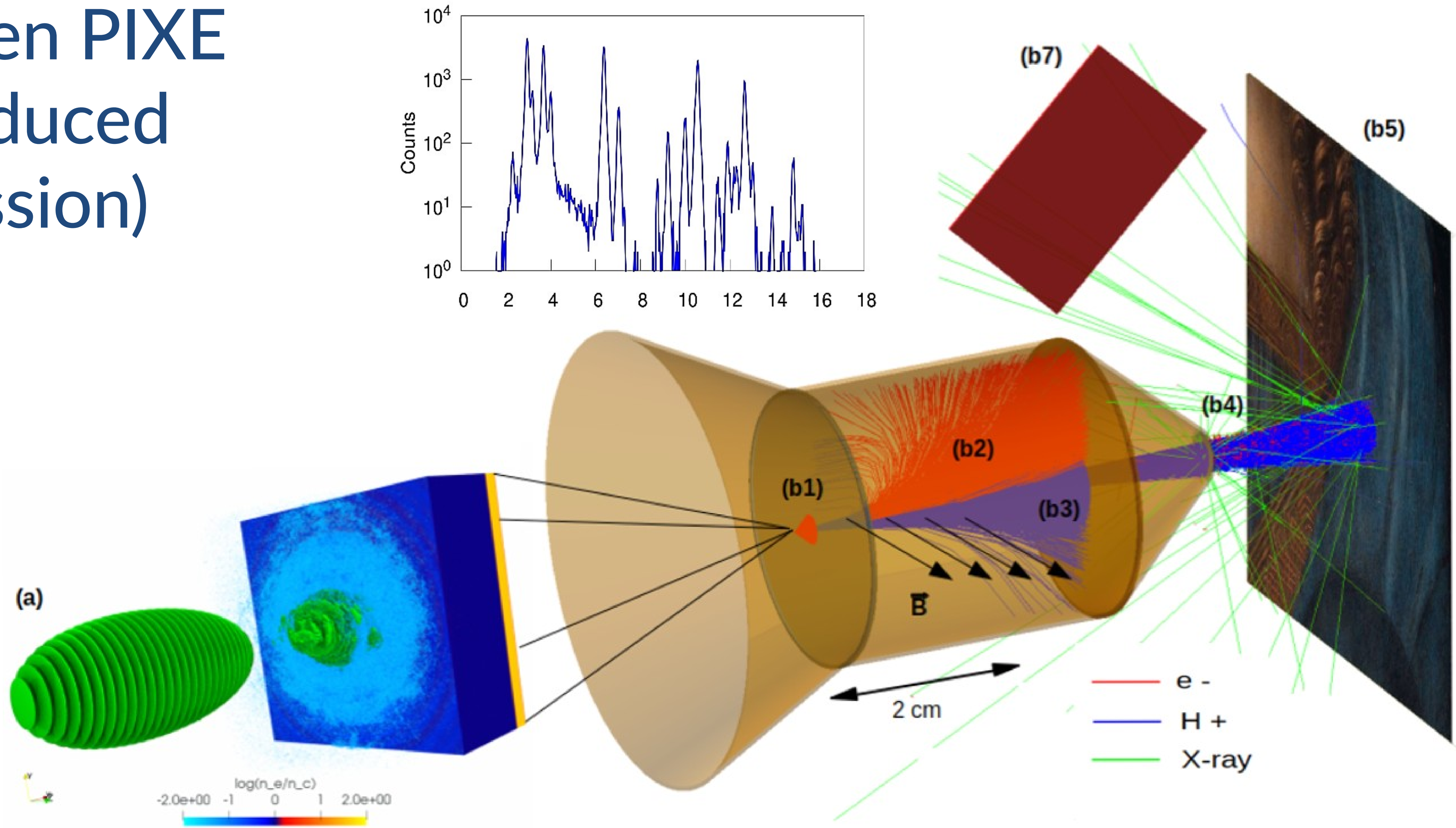


Why do we care?

Foam-attached targets could allow
to reduce size and cost of laser-driven ion accelerators

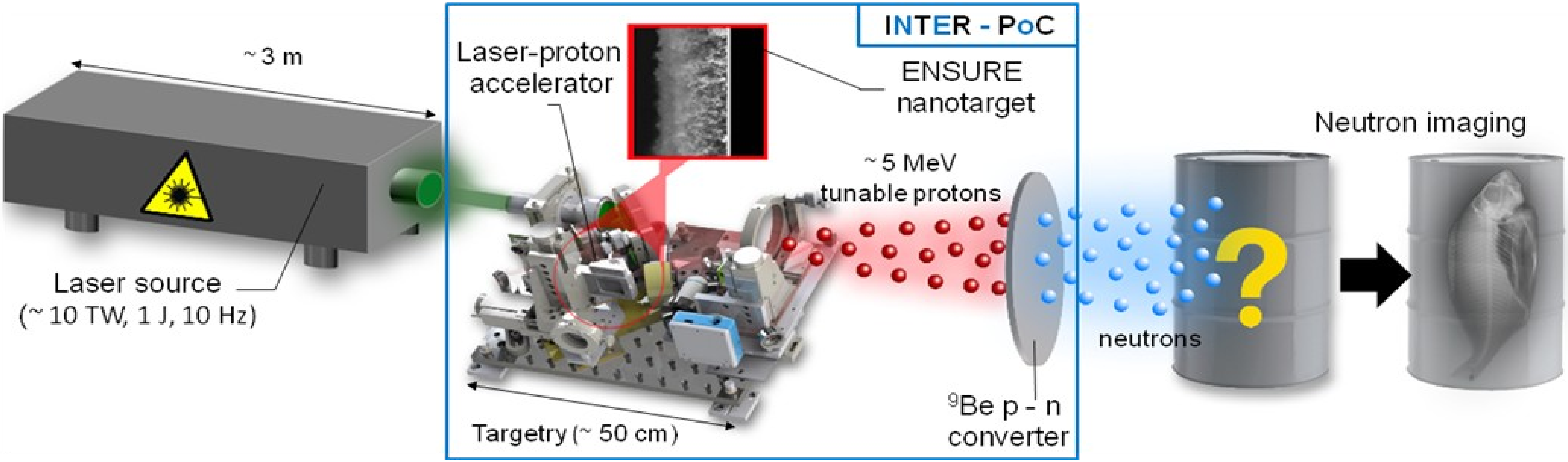
We are interested in applications
- requiring modest energies (few MeVs)
- without stringent requirements on energy spectra
- requiring modest proton fluxes

Laser-driven PIXE (Proton Induced X-ray Emission)

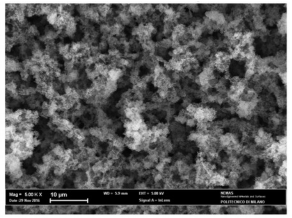


Passoni et al. Submitted to Scientific Reports (2018)

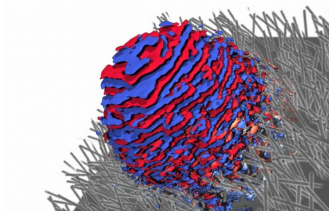
Compact laser-driven neutron sources



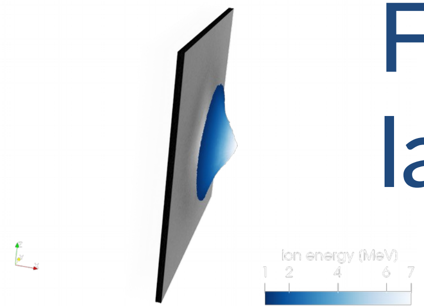
Conclusions



Low-density nanostructured foams are a promising material



Nanostructure might affect the interaction



Foam-attached targets allow to enhance laser-driven ion acceleration

Thank you for your time!
感謝諸位的時間

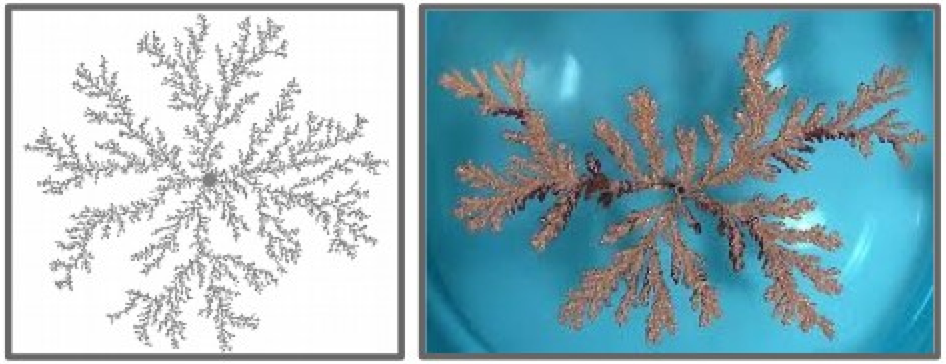
Follow us on our website!

https://www.ensure.polimi.it/

Backup slides

“Realistic” modeling based on DLA

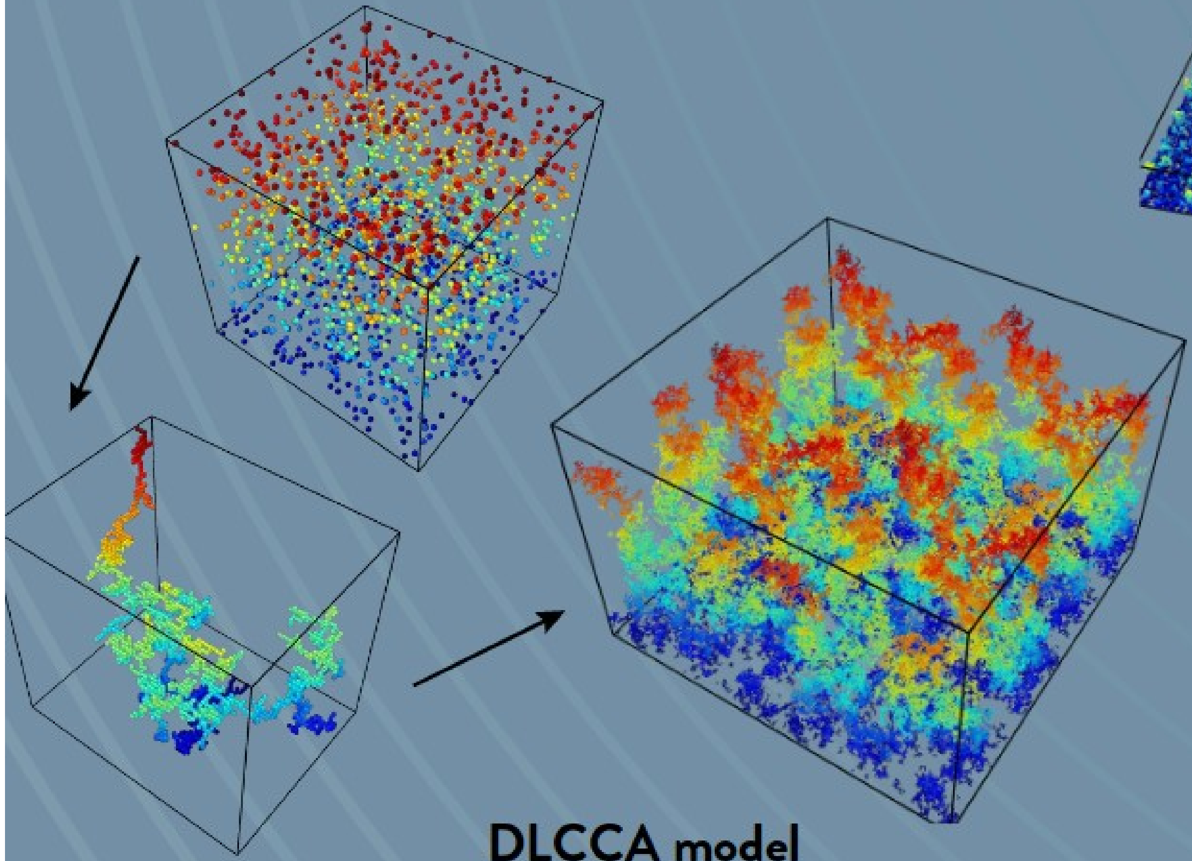
Diffusion Limited Aggregation (DLA)
A simple and very well studied model to reproduce structures resulting from aggregation phenomena.



Witten&Sander,PRL 47 , 1981

Diffusion-Limited Cluster-Cluster Aggregation (DLCCA)

Nanoparticles in Brownian motion
Cluster assembly by irreversible sticking
Cluster deposition on a substrate



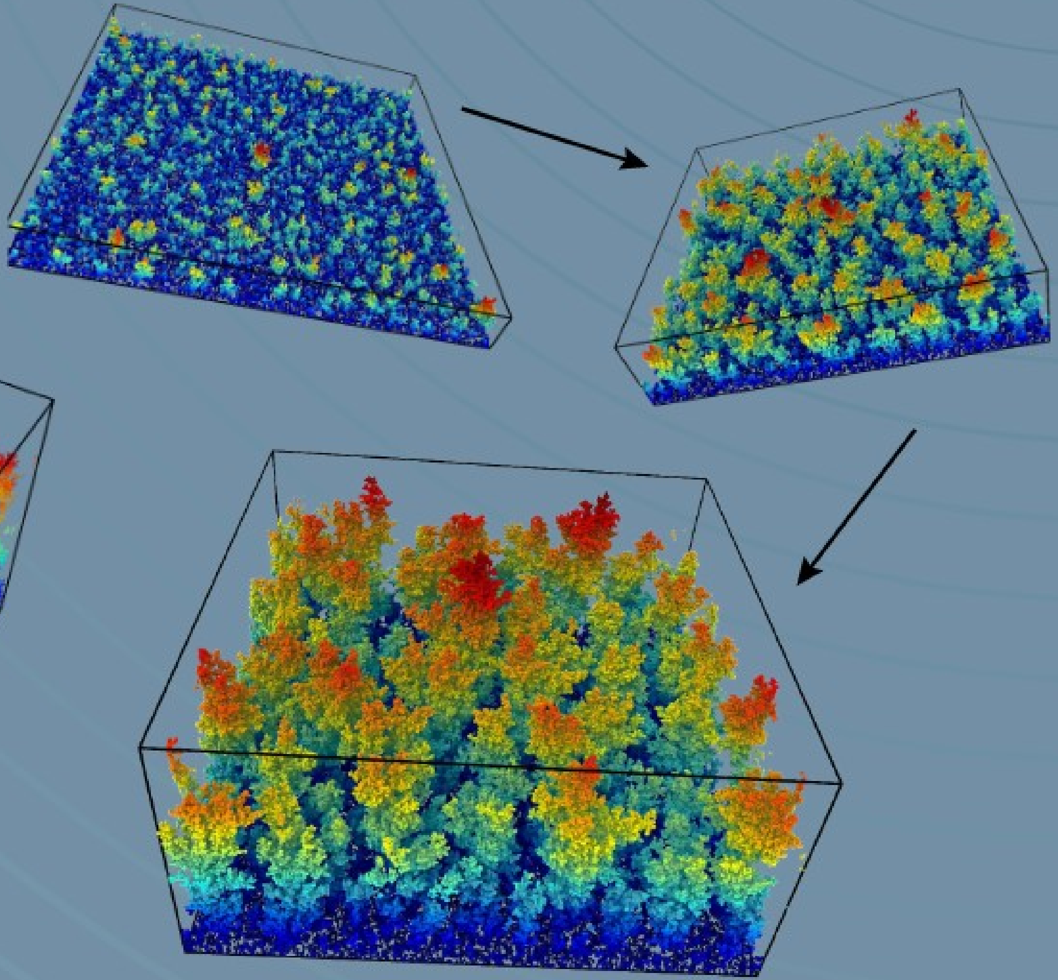
DLCCA model

Cross-section

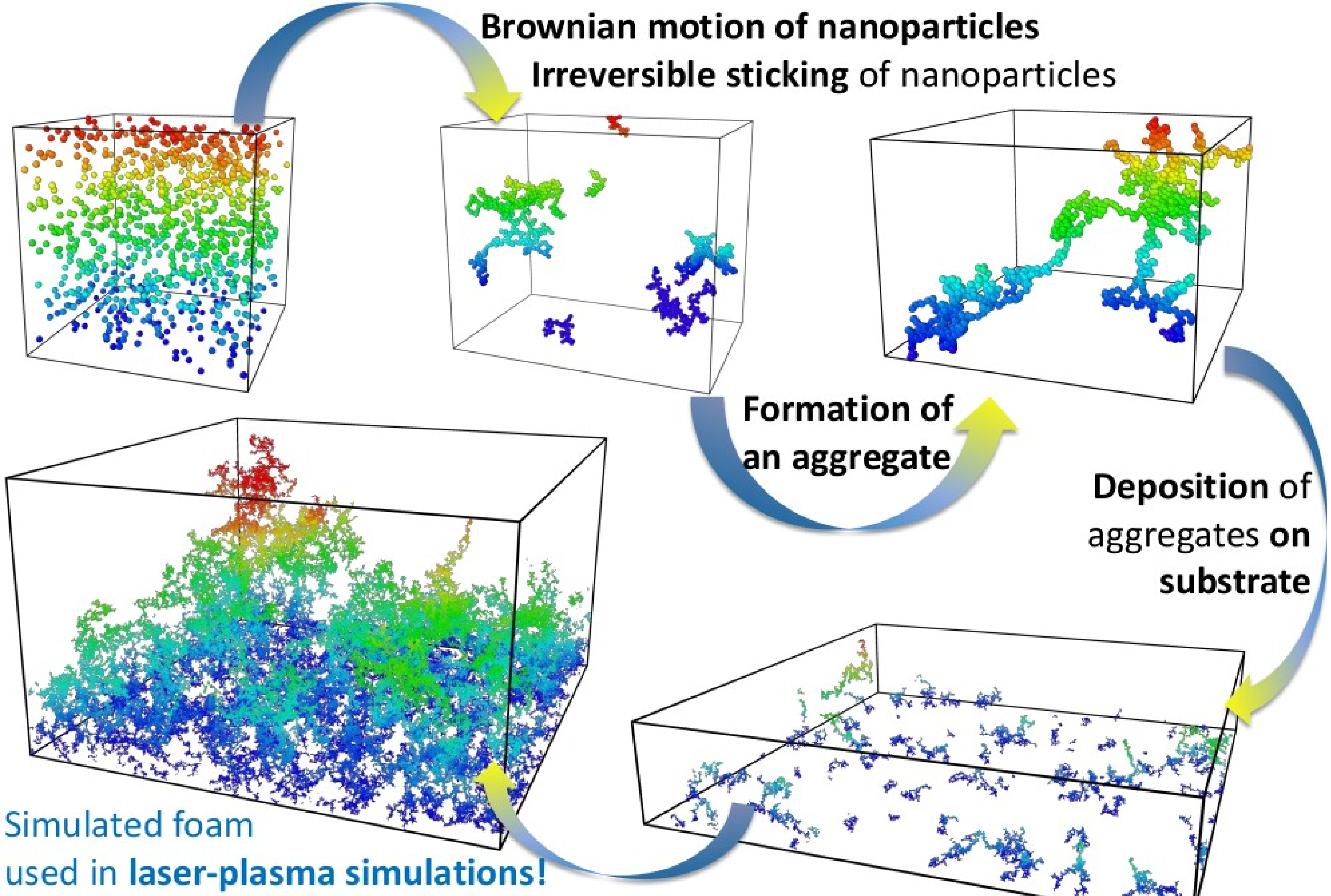
Top-view

Diffusion-Limited Aggregation (DLA)

Nanoparticles in Brownian motion one at a time
Irreversible sticking to substrate or to other particle



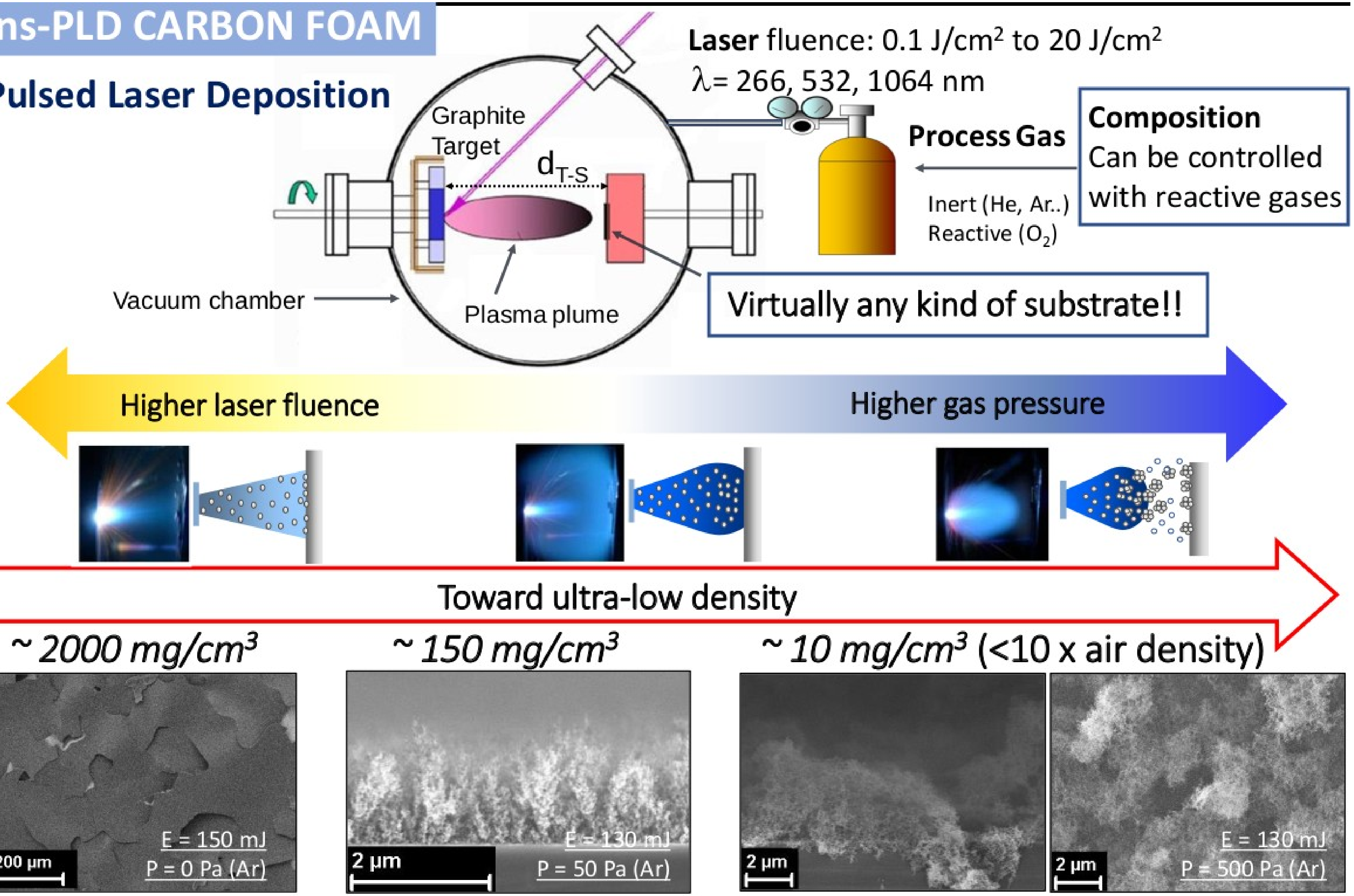
Diffusion Limited Cluster-Cluster Aggregation (DLCA)



Fedeli, L., Formenti, A., Cialfi, L., **Pazzaglia, A.**, & Passoni, M. (2018). Ultra-intense laser interaction with nanostructured near-critical plasmas. *Scientific reports*, *8*(1), 3834.

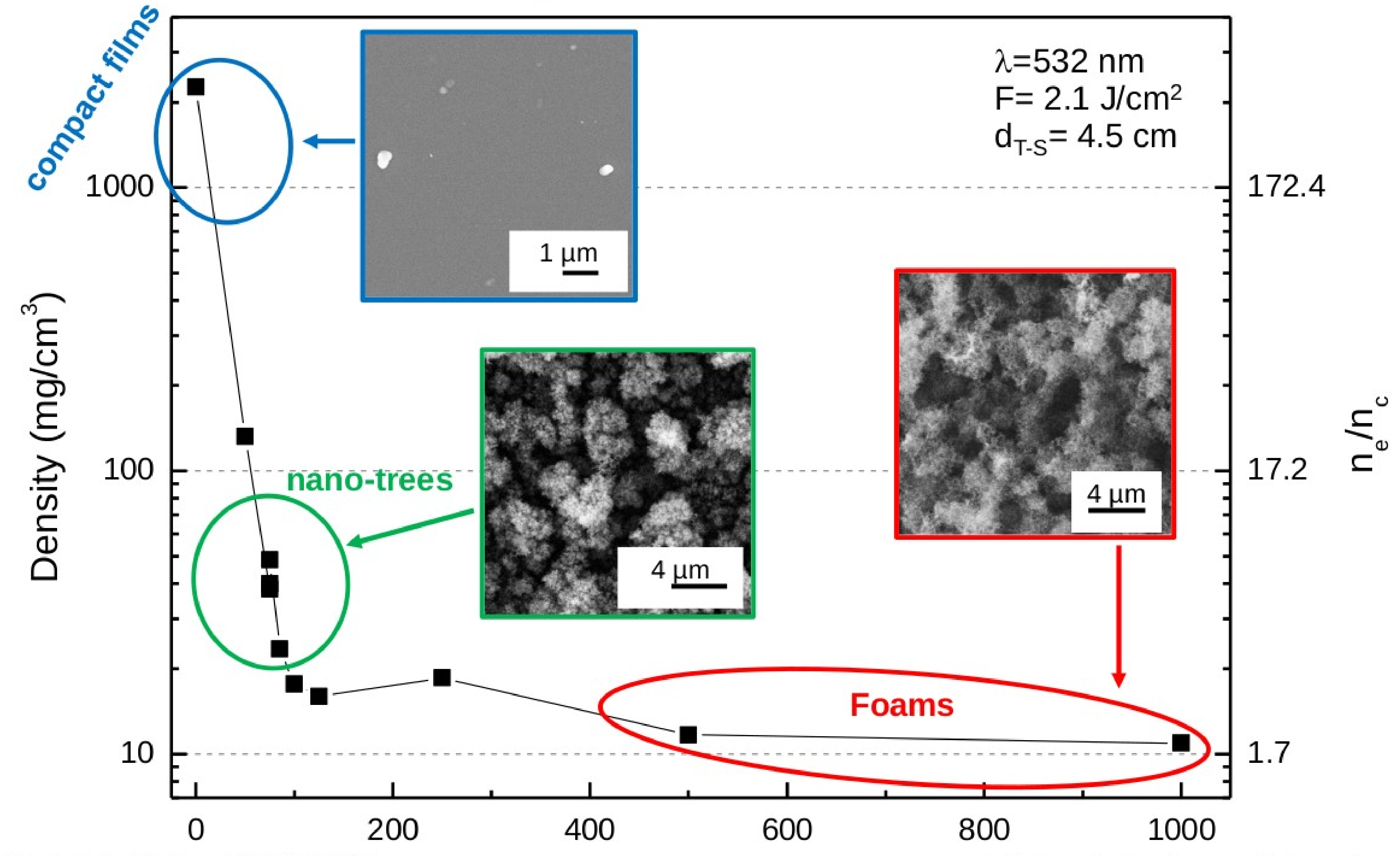
ns-PLD CARBON FOAM

Pulsed Laser Deposition



Zani, A., et al. "Ultra-low density carbon foams produced by pulsed laser deposition." Carbon 56 (2013): 358-365.

How to produce carbon foams

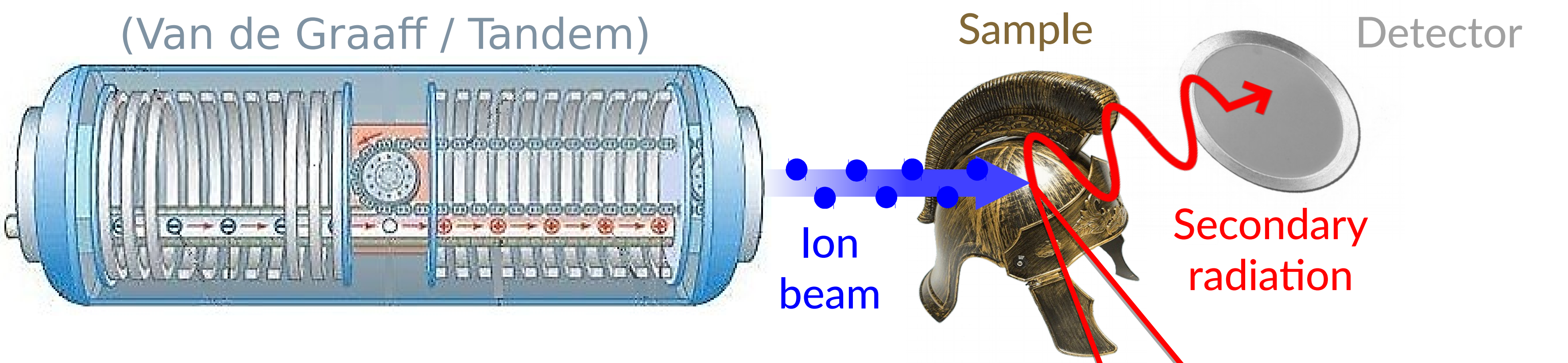


A. Zani et al., *Carbon*, **56** 358 (2013)

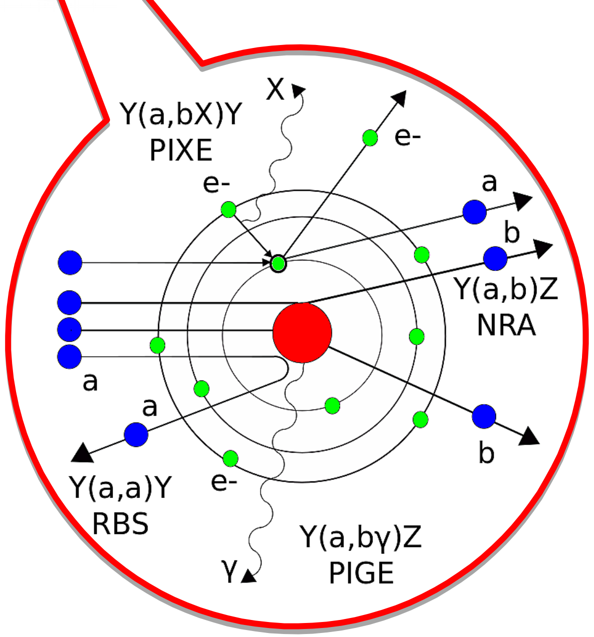
I. Prencipe et al., *Sci. Technol. Adv. Mater*. **16** (2015)

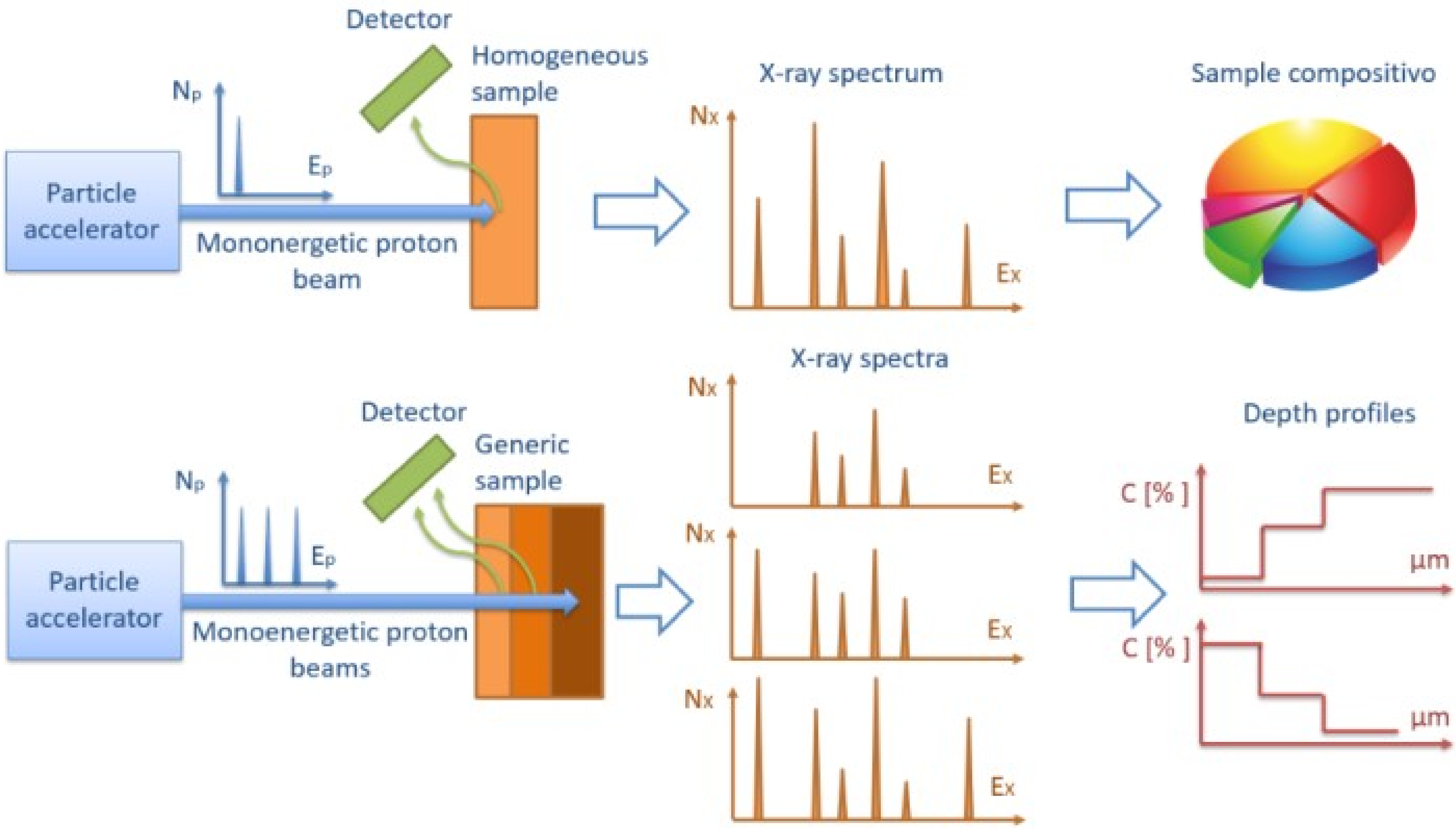
A. Maffini et al., *On the growth dynamics of low-density carbon foams*, in preparation

Ion Beam Analysis (IBA)

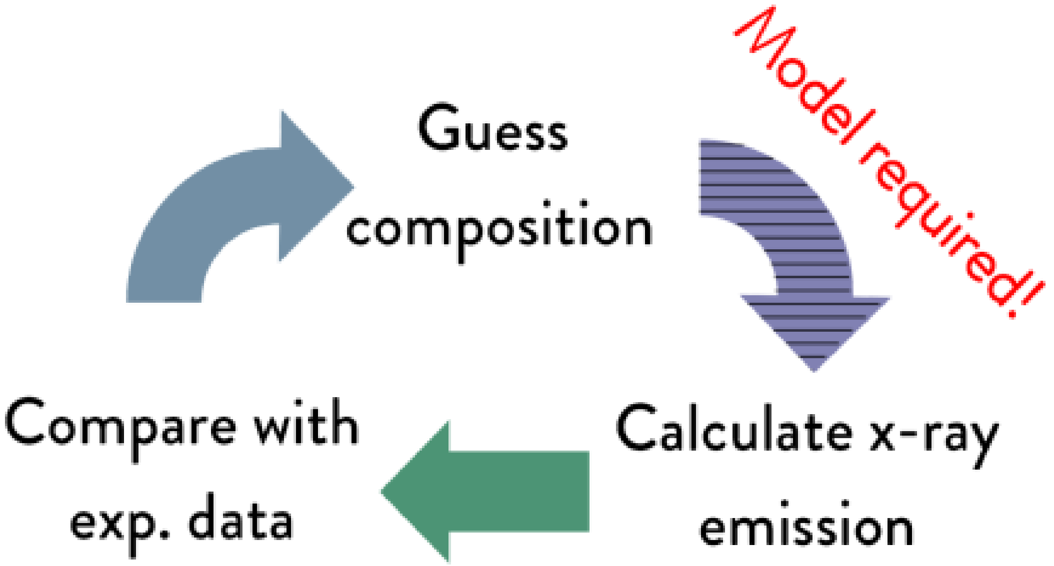


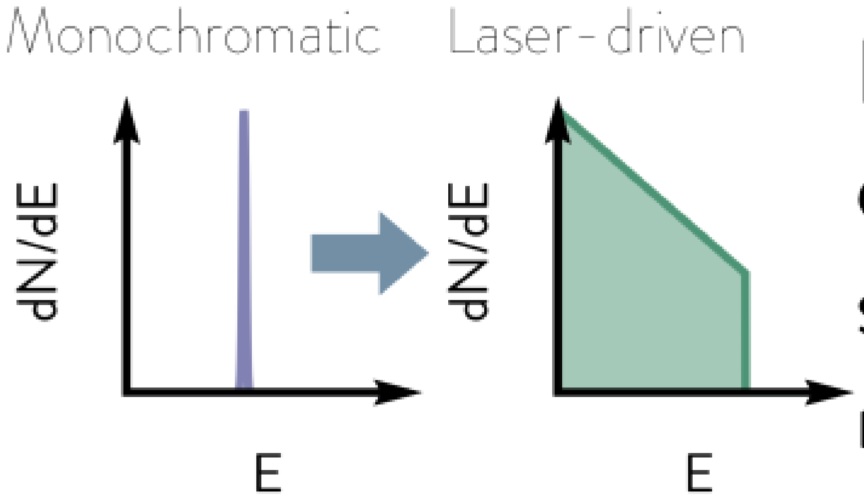
- **2-5 MeV/u** monoenergetic **ions**.
- Low currents (**~ 100 pA**)
- Elemental **concentrations** & **Depth profiles**
- **Cultural heritage**, environmental and biological and medical studies.




Detector
Homogeneous sample
Np
Ep
Particle accelerator
Mononergetic proton beam
X-ray spectrum
Nx
Ex
Sample compositivo
Detector
Generic sample
Np
Ep
Particle accelerator
Monoenergetic proton beams
X-ray spectra
Nx
Ex
Nx
Ex
Nx
Ex
Depth profiles
C [%]
µm
C [%]
µm

PIXE relies on an iterative process to reconstruct sample compositions and elemental depth profiles from x-ray yields.





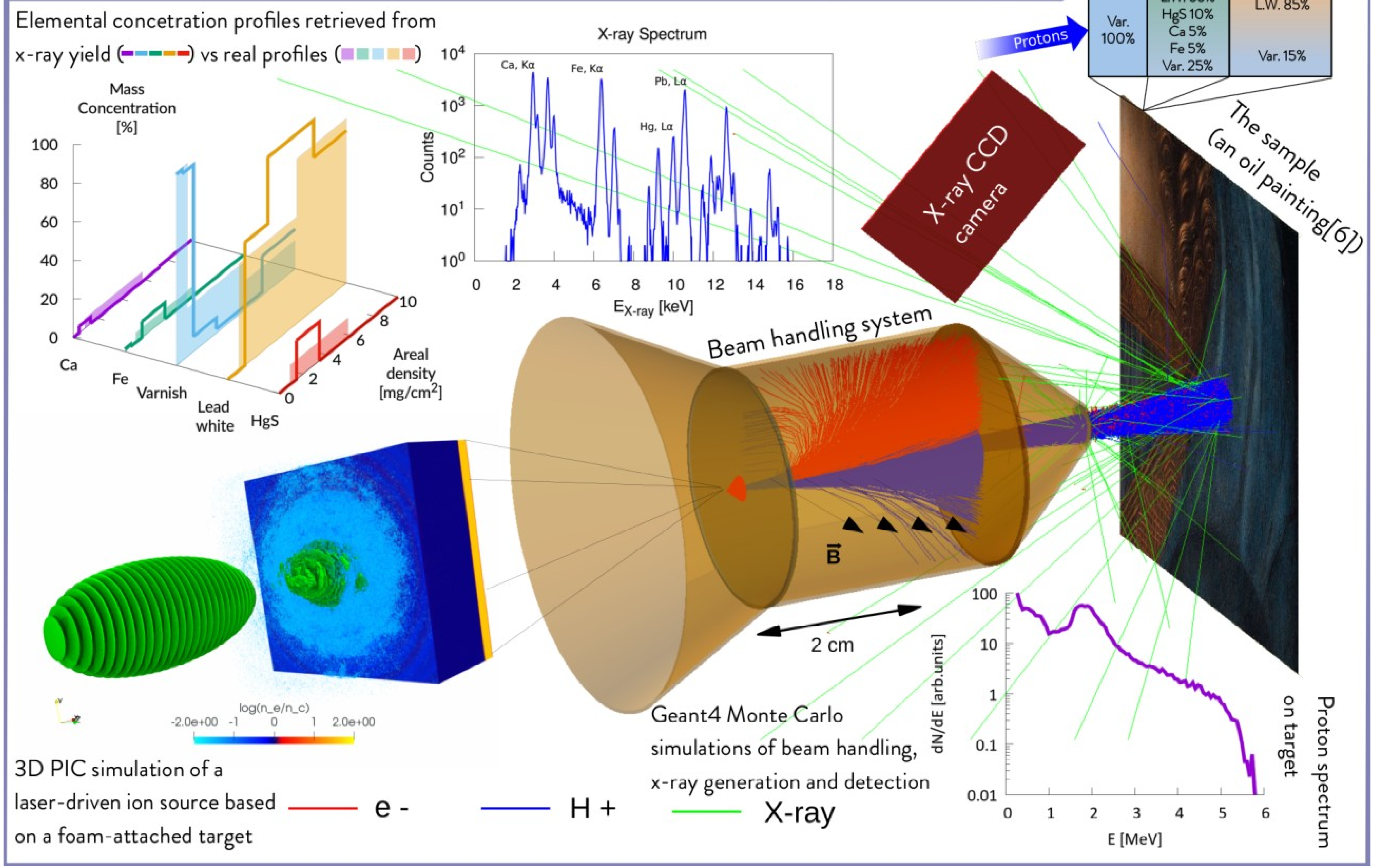
Existing PIXE theory has been developed for monochromatic sources, thus modifications are needed for laser-driven PIXE[5]

$$Y_i = N_p \frac{\Delta\Omega}{4\pi} \varepsilon_i \frac{N_{av}}{M_i} W_i \int_{E_0}^{E_f} \sigma_i(E) \omega_i e^{-\mu_i \int_{E_0}^{E'} \frac{dE'}{S(E')} \frac{\cos\theta}{\cos\phi}} \frac{dE}{S(E)} \Rightarrow$$

$$Y_i = \frac{\Delta\Omega}{4\pi} \varepsilon_i \frac{N_{av}}{M_i} W_i \int_{E_{p,min}}^{E_{p,max}} f_p(E_p) \int_{E_p}^{0} \sigma_i(E) \omega_i e^{-\mu_i \int_{E_p}^{E'} \frac{dE'}{S(E')} \frac{\cos\theta}{\cos\phi}} \frac{dE}{S(E)} dE_p$$

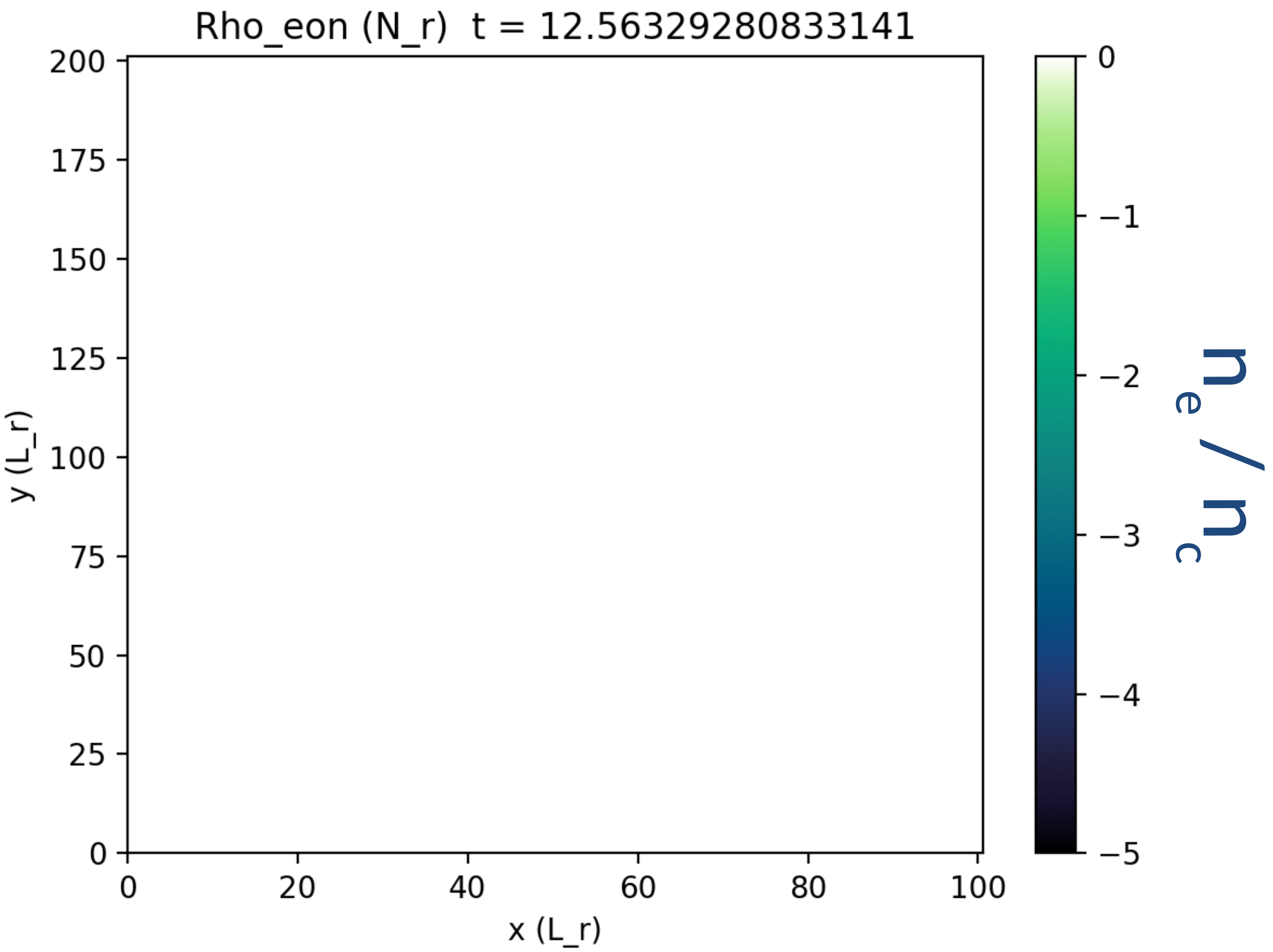
Yi: x-ray yield. ΔΩ: subtended solid angle, εi: detector efficiency, Nav: Avogadro's number, Ef: final proton energy, σi(E): ionization cross section, ωi: fluorescence yield, S(E): proton stopping power, σi: X-ray attenuation coefficient, θ: proton impact angle, φ: X-ray emission angle, fp(Ep): proton energy distribution (Ep,min and Ep,max : lower and upper cut-offs)

A simulated laser-driven differential-PIXE experiment[5]



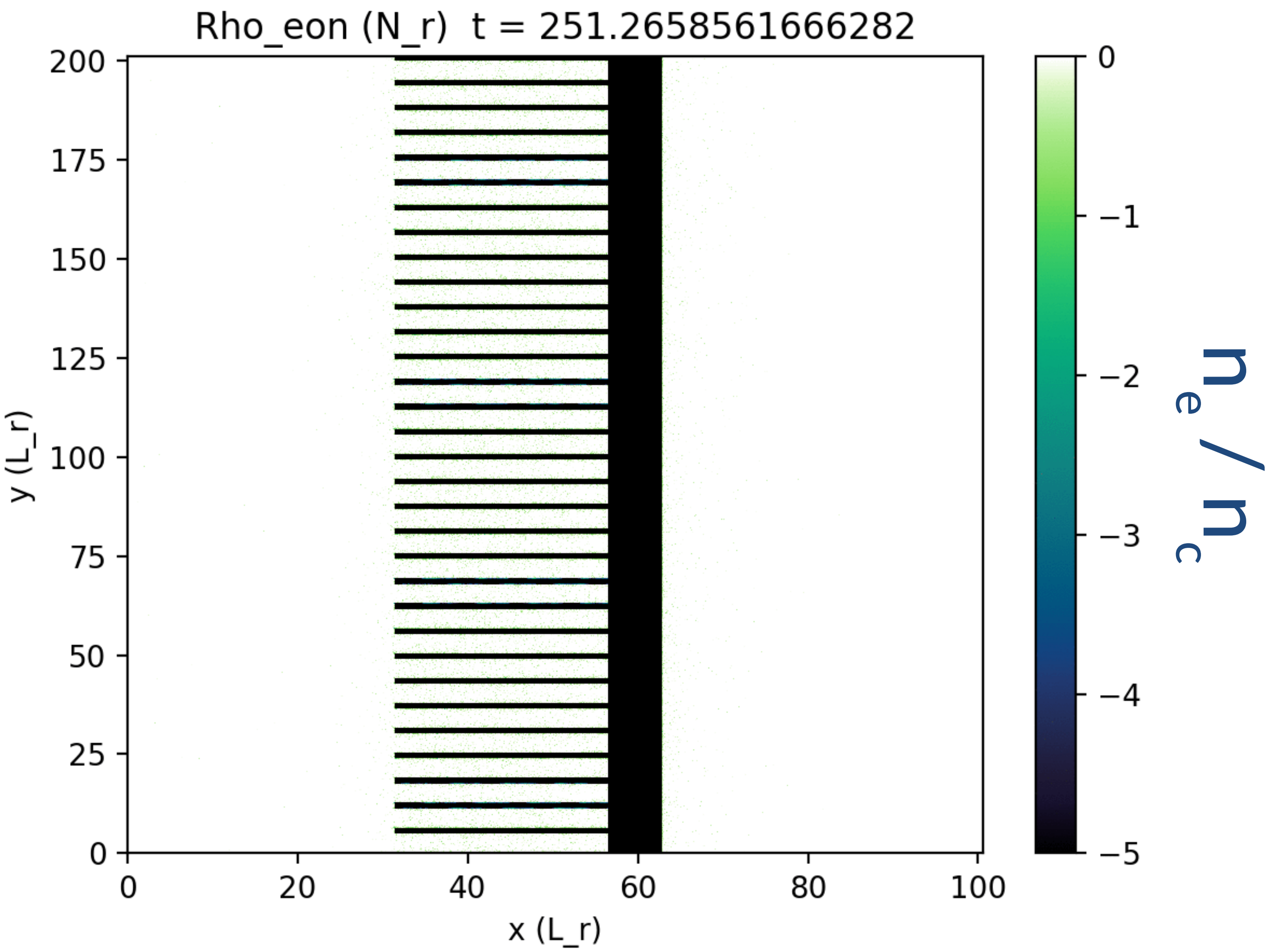
2D simulations with $a_0 = 0.05$ impinging onto a nanowire target

T ~ 5 fs



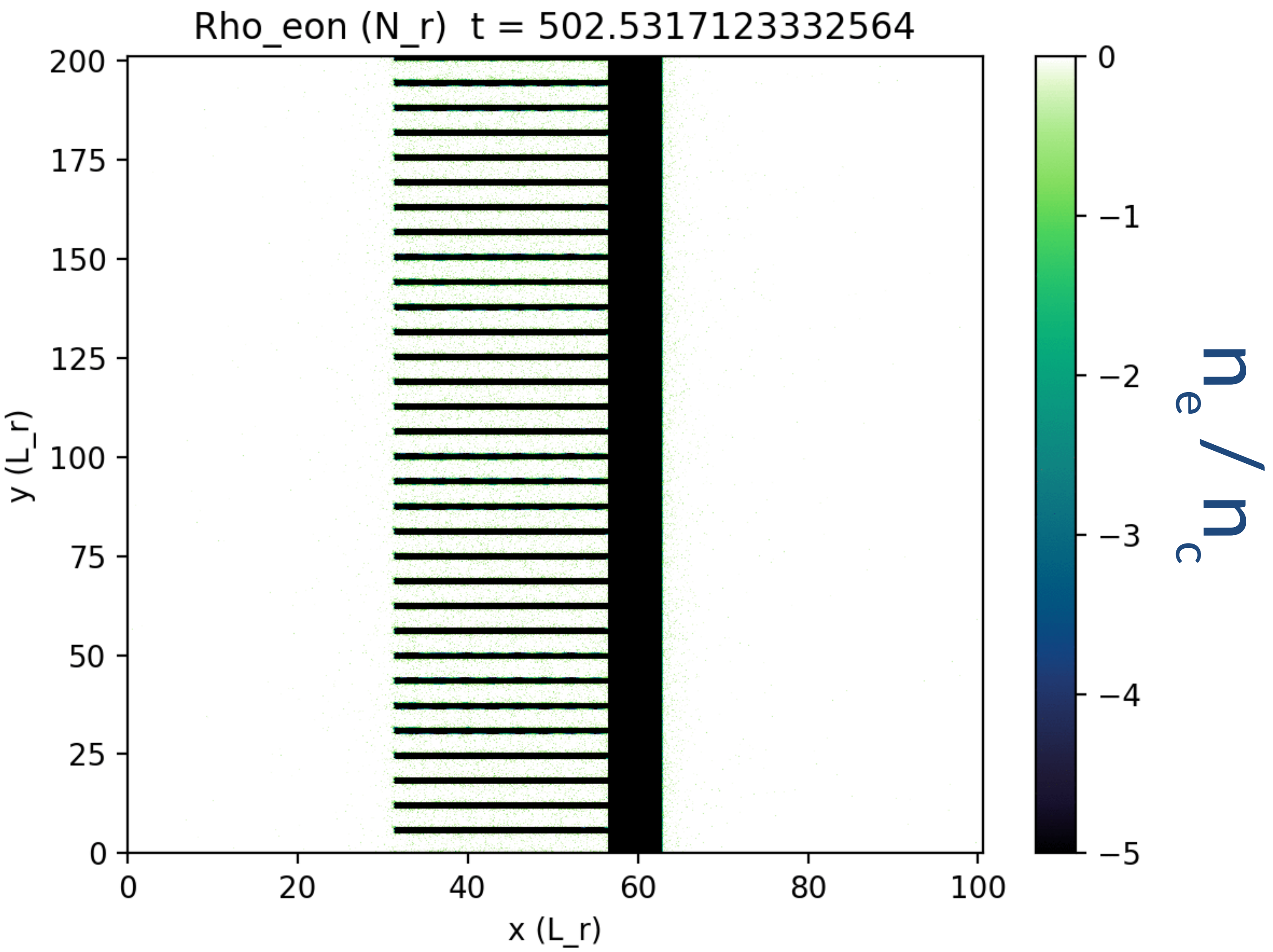
2D simulations with $a_0 = 0.05$ impinging onto a nanowire target

T ~ 107 fs



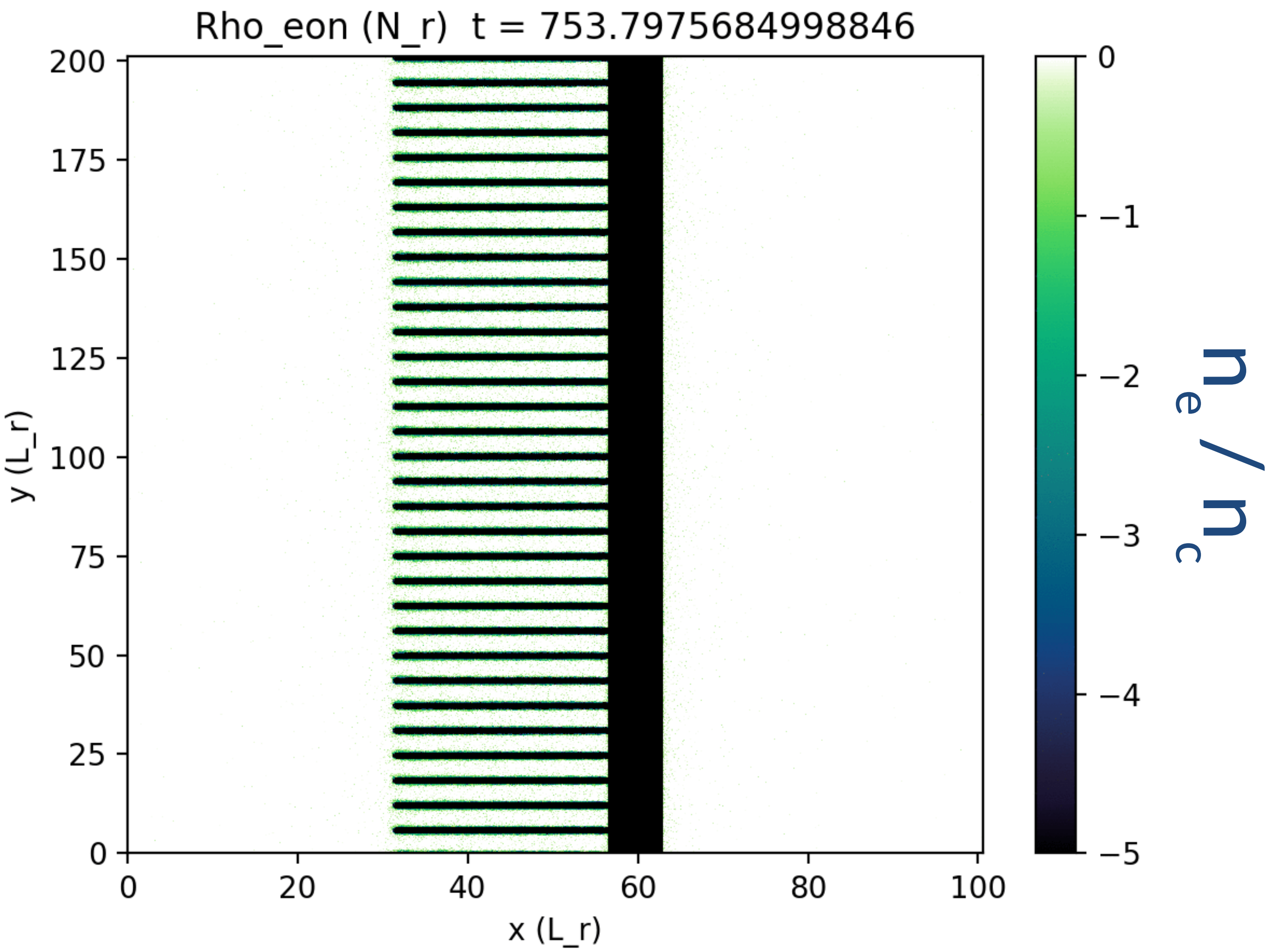
2D simulations with a_0 = 0.05 impinging onto a nanowire target

T ~ 213 fs



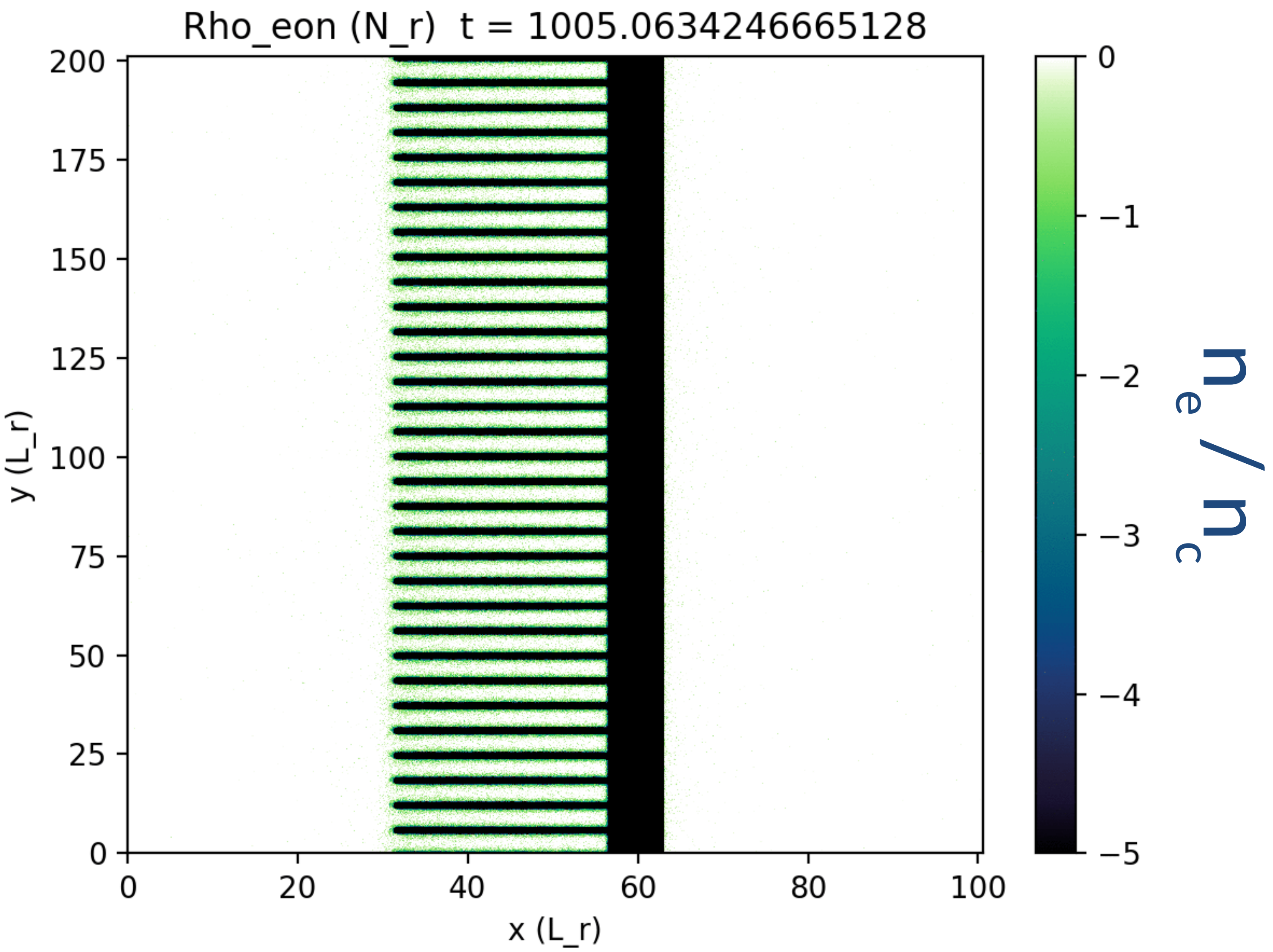
2D simulations with a_0 = 0.05 impinging onto a nanowire target

T ~ 320 fs



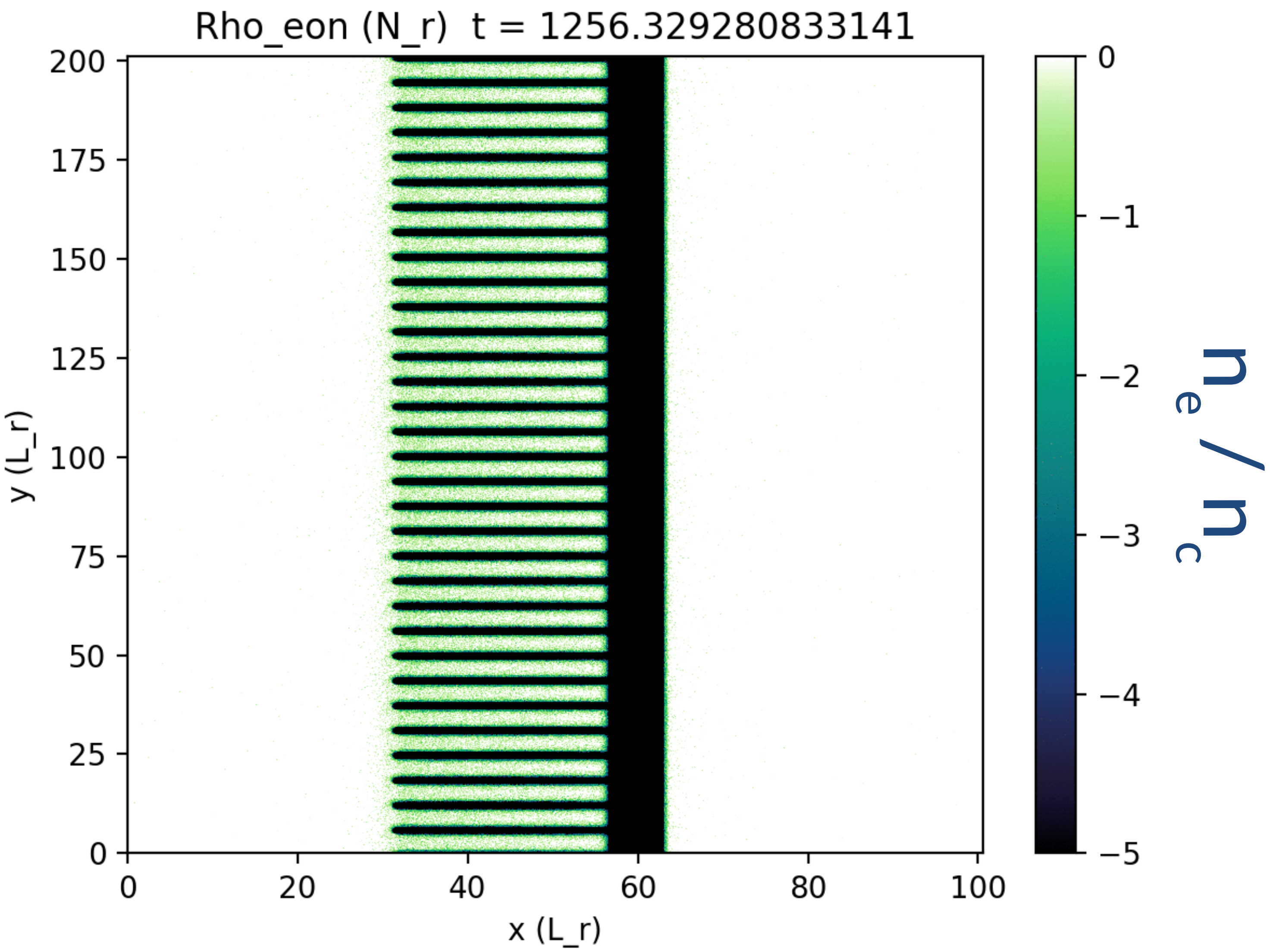
2D simulations with $a_0 = 0.05$ impinging onto a nanowire target

T ~ 427 fs



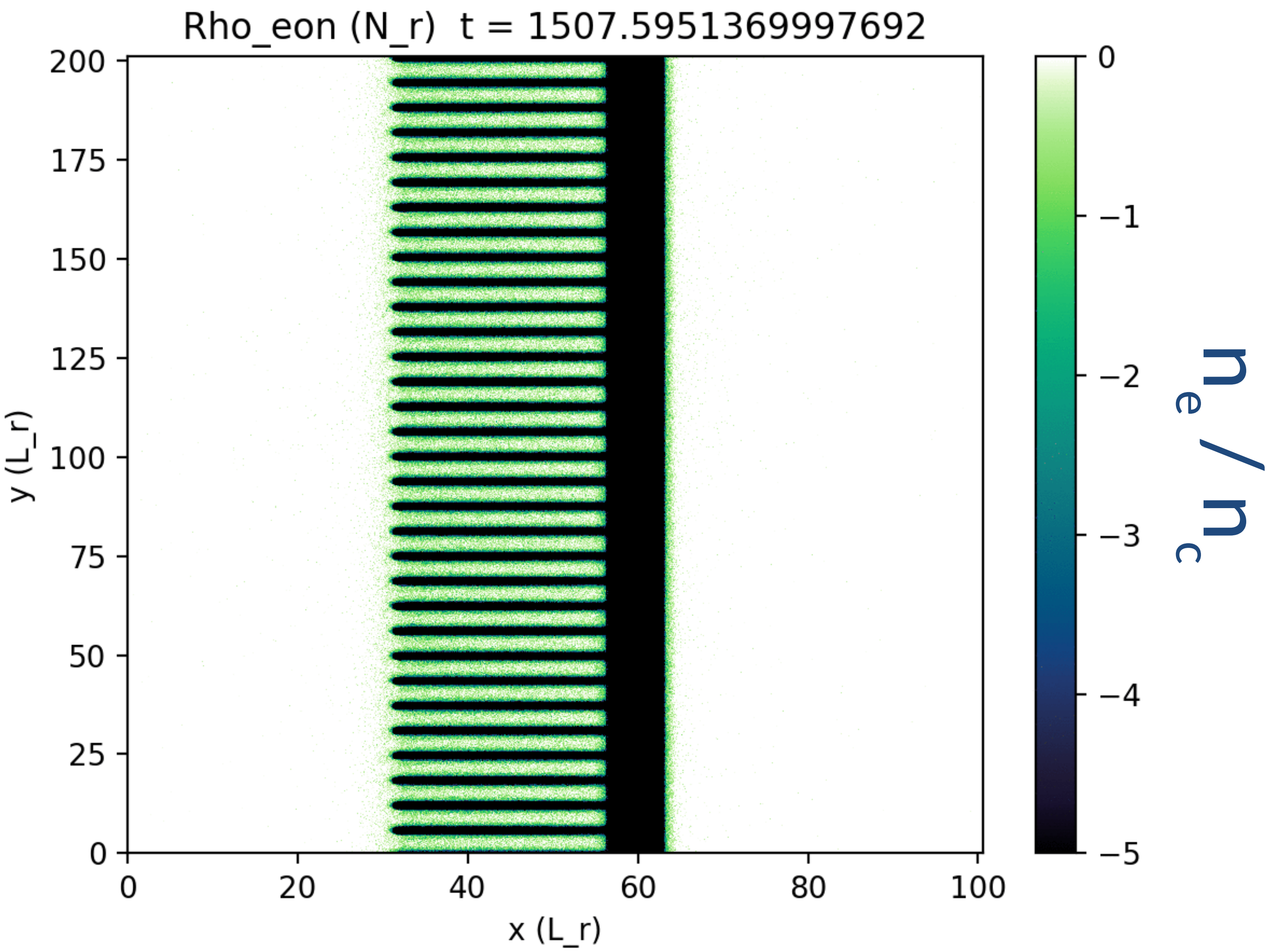
2D simulations with a_0 = 0.05 impinging onto a nanowire target

T ~ 533 fs



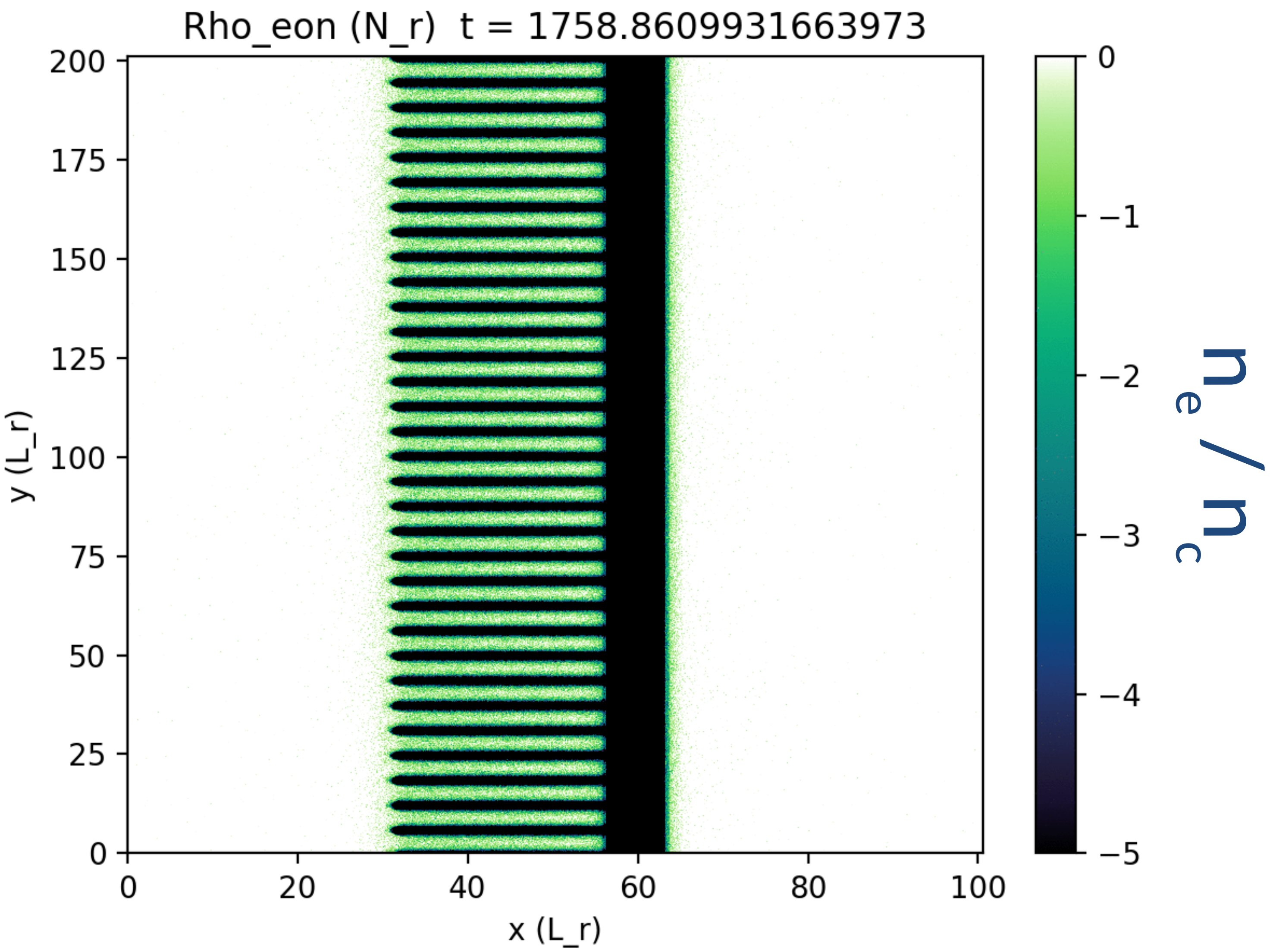
2D simulations with $a_0 = 0.05$ impinging onto a nanowire target

T ~ 640 fs



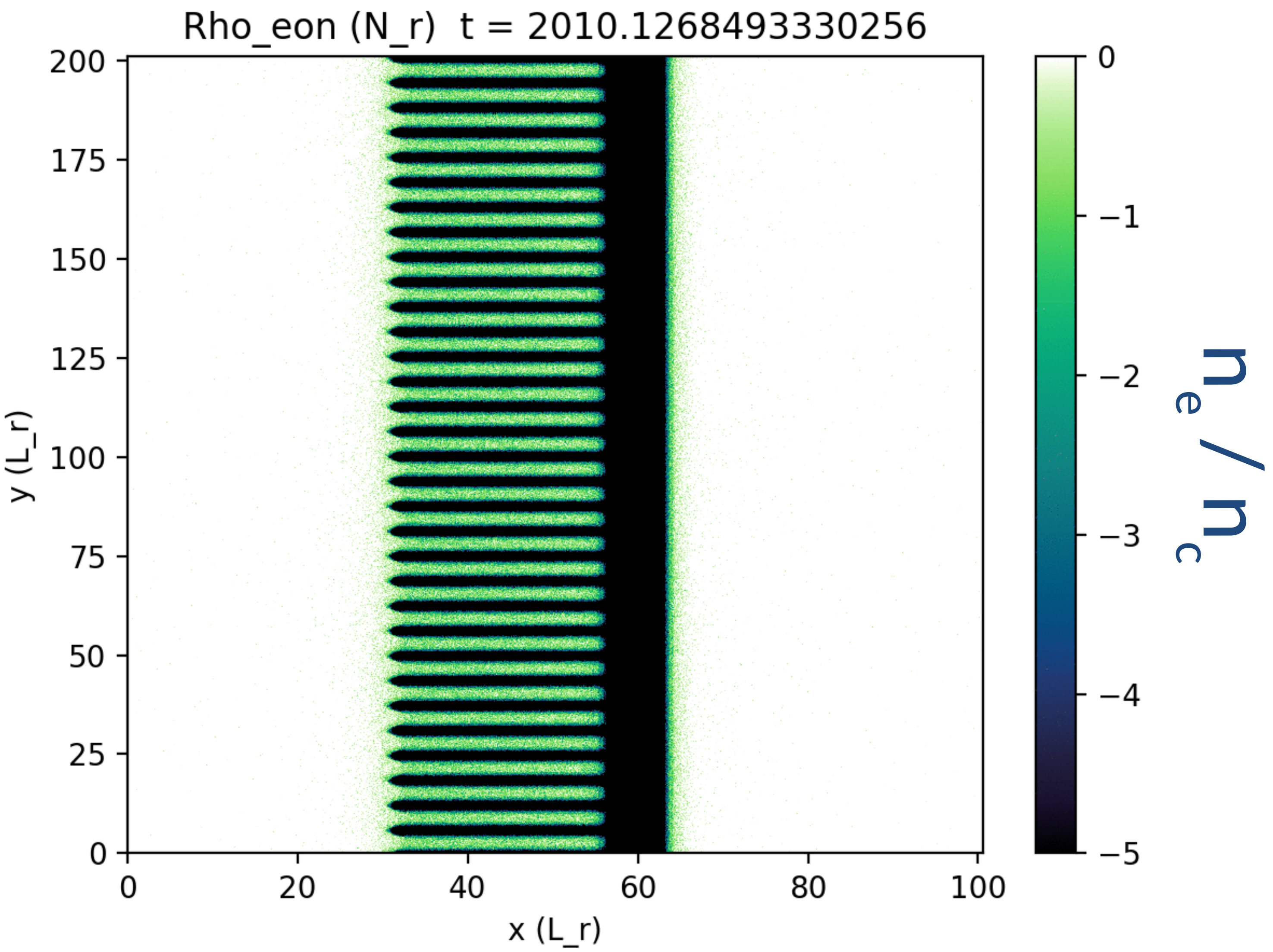
2D simulations with a_0 = 0.05 impinging onto a nanowire target

T ~ 746 fs



2D simulations with $a_0 = 0.05$ impinging onto a nanowire target

T ~ 853 fs



2D simulations With a0 = 0.05 impinging onto a nanowire target

T ~ 960 fs