CMD30
FisMat 2023

joint conference
Milano - September 4-8, 2023

Mini-colloquium: Italian Plasma Physics

Carbon nanofoam targets for inertial confinement fusion experiments

A. Maffini[1], M. Cipriani[2], D. Orecchia[1], M. S. Galli de Magistris[1], V. Ciardiello[3], V. P. Lo Schiavo[3], D. Davino[3], G. Cristofari[2], M. Scisciò[2], F. Consoli[2], M. Passoni[1]

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[2] ENEA

[3] UNIVERSITÀ DEGLI STUDI DEL SANNIO DNS VICTORIA BENEVENTO

EUROfusion
ENR-IFE.01.CEA
"Advancing shock ignition for direct-drive inertial fusion"

Foam targets in laser-matter interaction

Why carbon nanofoams?

Features of PLD carbon nanofoams

Carbon nanofoams for ICF experiments

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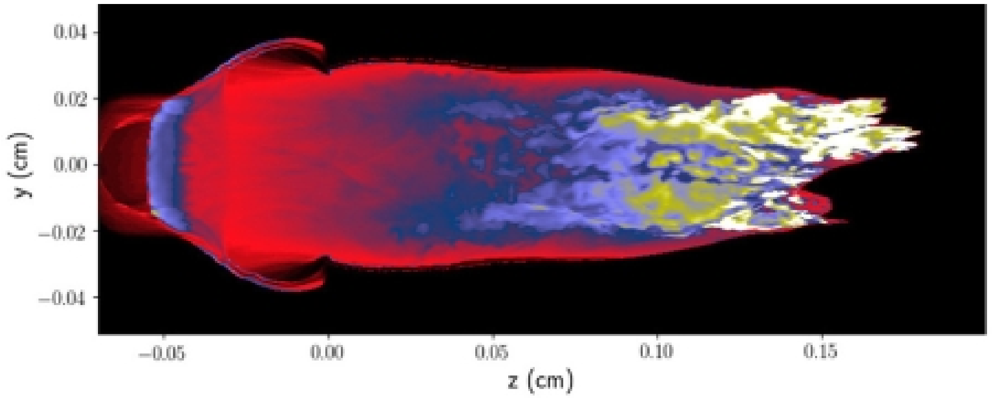
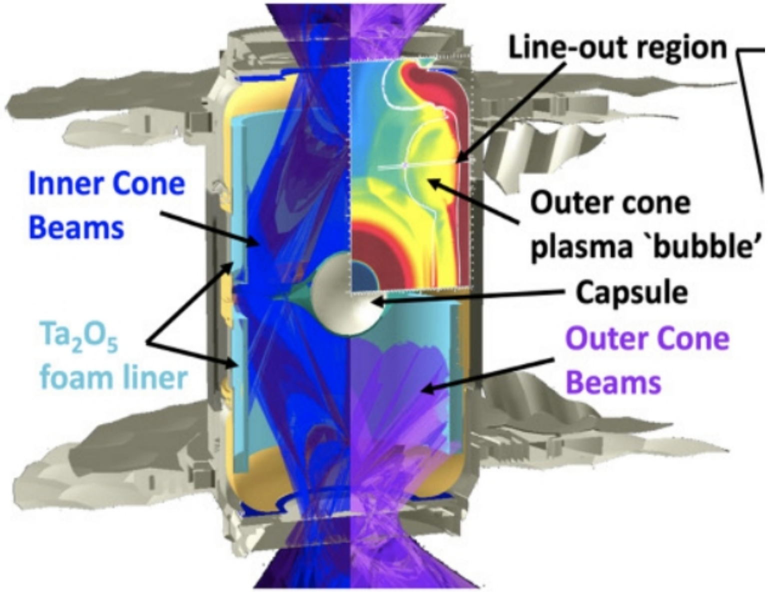
- Increased laser conversion into mechanical energy (shock waves)
- Smoothing of laser non-homogeneity in ICF
- Warm dense matter (EOS, astrophysics,...)



M. A. Belyaev, et al., *Phys. Plasmas* **27**, 112710 (2020)



- Bright x-ray sources (e.g. in hohlraum internal walls)
- Increased laser conversion into secondary radiation (electrons, ions, neutrons, x-rays, ...)

A.S. Moore, *Phys. Review E* **102**, 051201(R) (2020)

M. Passoni et al., *Plasma Phys. Control. Fusion* **62** (2019)

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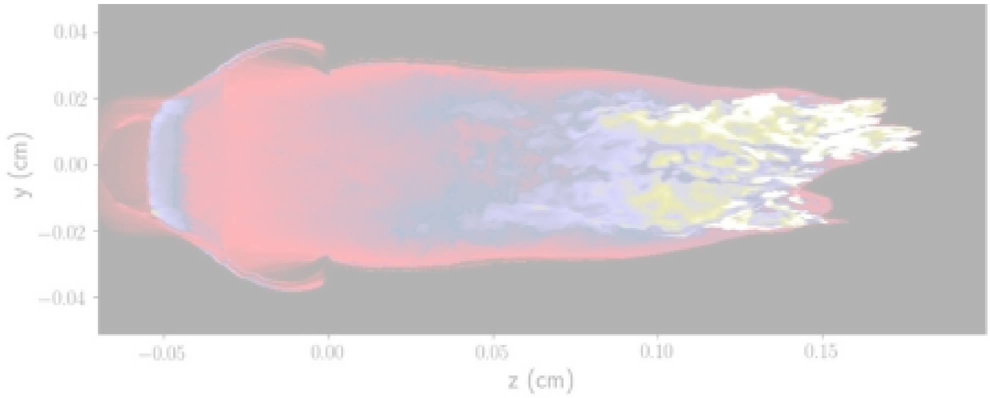

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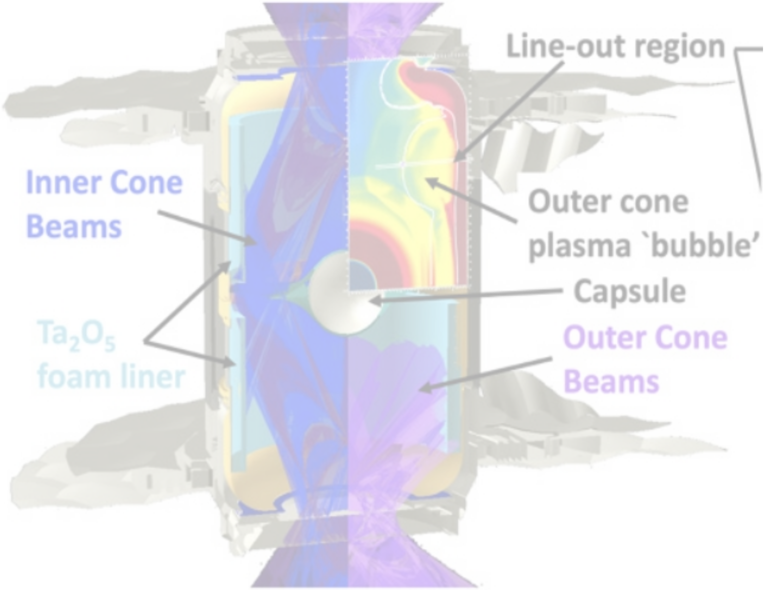

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NanoLab

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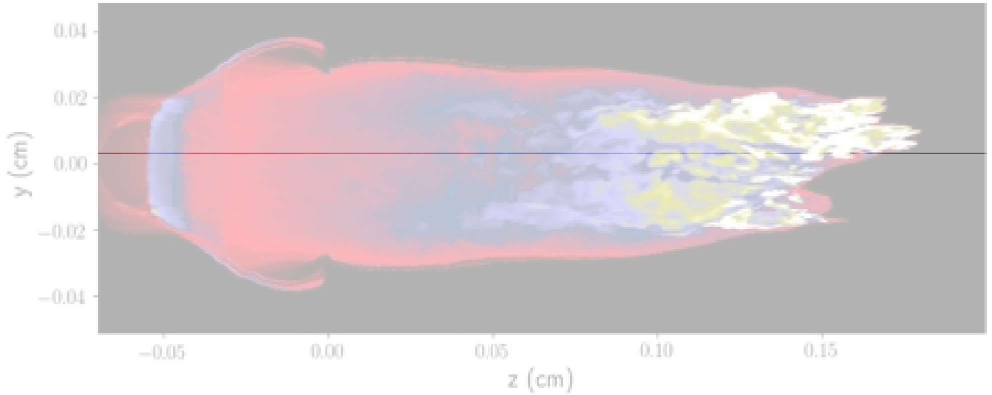

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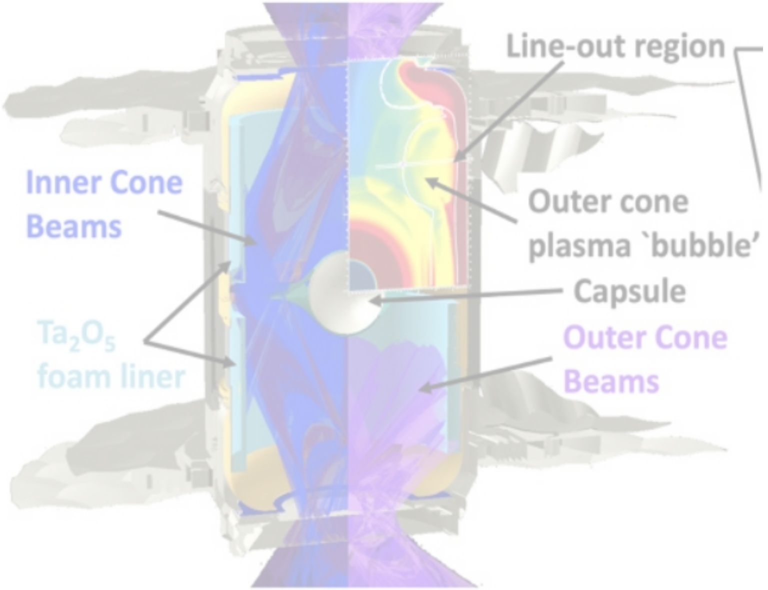

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NanoLab

Conventional foams for ICF experiments

A review of low density porous materials used in laser plasma experiments

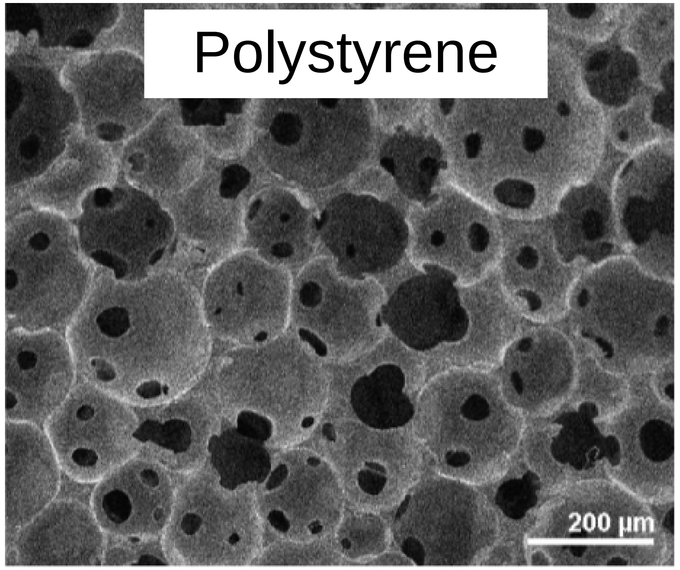
Cite as: Phys. Plasmas **25**, 030501 (2018); https://doi.org/10.1063/1.5009689
Submitted: 19 October 2017 • Accepted: 20 February 2018 • Published Online: 16 March 2018

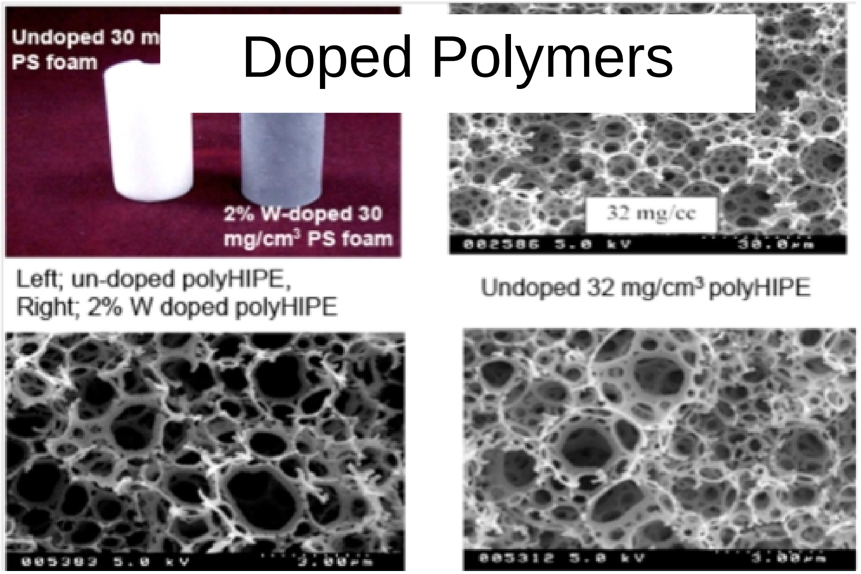
Keiji Nagai, Christopher S. A. Musgrave and Wigen Nazarov

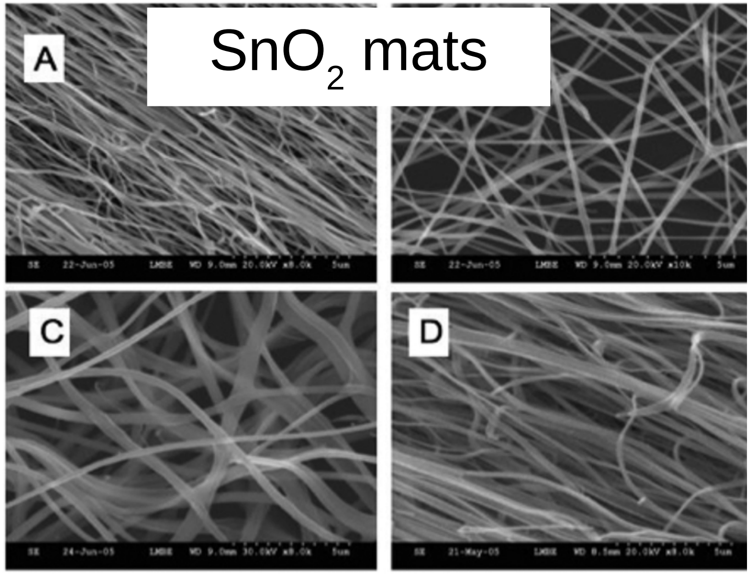
TABLE I. Foam types used in laser targets and their properties.

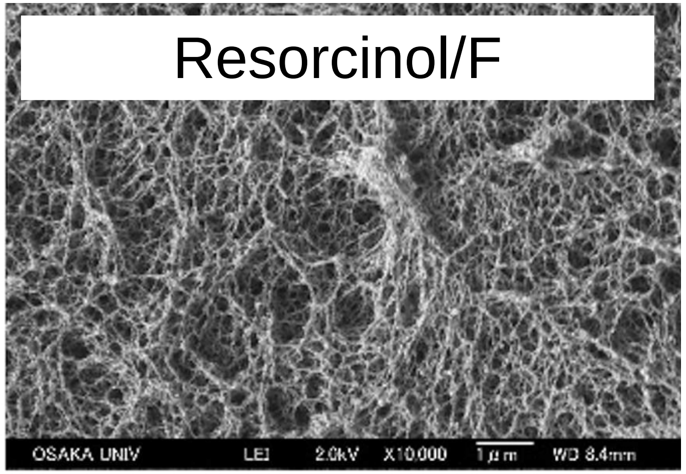
Foam class	Pore size range[a]	Density range (mg/cm^3)[b]	Element composition	High/low Z (e1)	Target dimensions (μm)
Aerogels					
Organic aerogels (RF)	nm	10–250	CHO	Low Z	200–600
Inorganic aerogels	nm	1–250	(Si, Ta, Ga, Al) O_2	Middle-High Z	200–600
Carbonized aerogels	nm	10–250	C	Low Z	200–600
PolyHIPE	μm	30–250	CH	Low Z	200–600
Acrylates and Methacrylates	μm	5–250	CHO	Low Z	10–600
Templated foams	nm-μm	1–250	Metal oxides	High Z	10–600
Electrospinning	nm	1–250	Metal oxides	High Z	10–600
Poly(3-methyl-1-pentene)	nm-μm	3–250	CH_2	Low Z	200–600

Conventional foams for ICF experiments



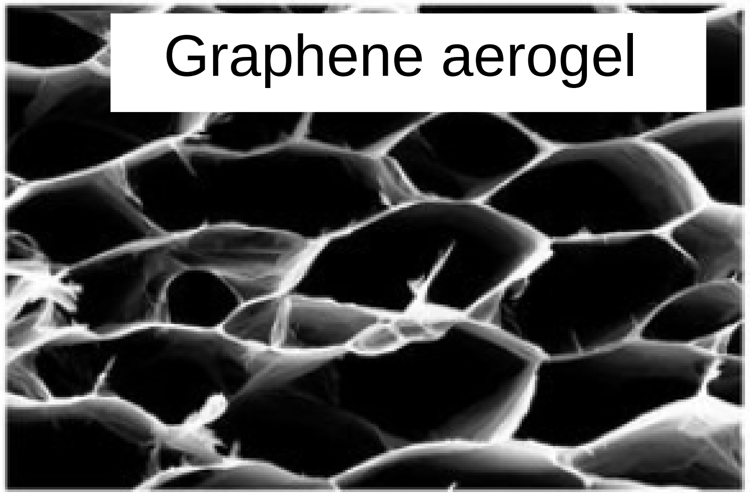






- Quasi-periodic networks
- Characterized by “pore size”

K. Nagai, et al., *Physics of Plasmas* **25**, 030501 (2018)
C. Yang et., *Appl. Phys. Lett*. **115**, 111901 (2019)
Y. Kaneyasu et al., *High Pow. Las. Sci. Eng.* **9** (2021), e31



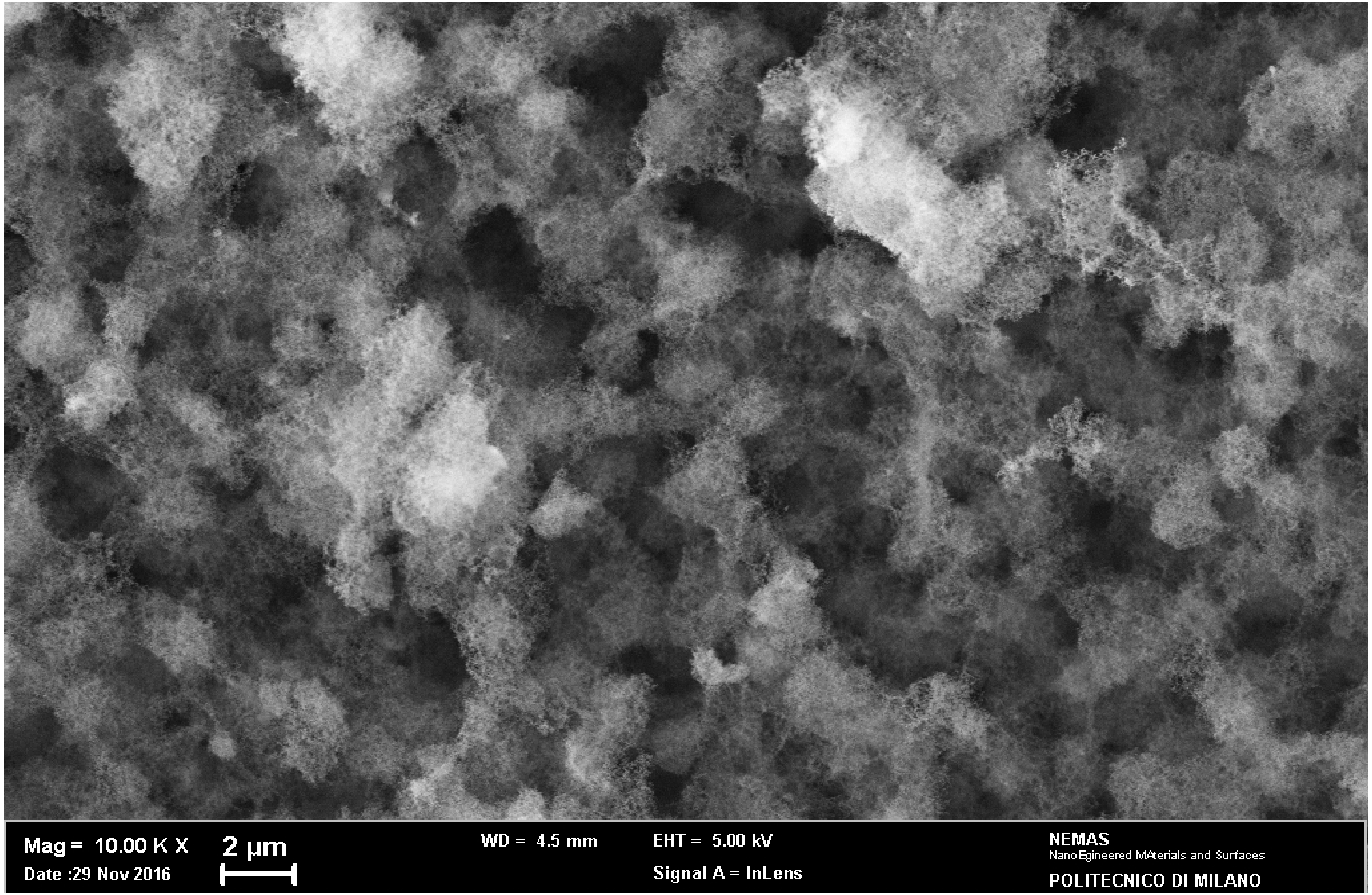
Why foam targets in laser-matter interaction?

Why carbon nanofoams?

Features of PLD carbon nanofoams

Carbon nanofoams for ICF experiments

Carbon nanofoams are different



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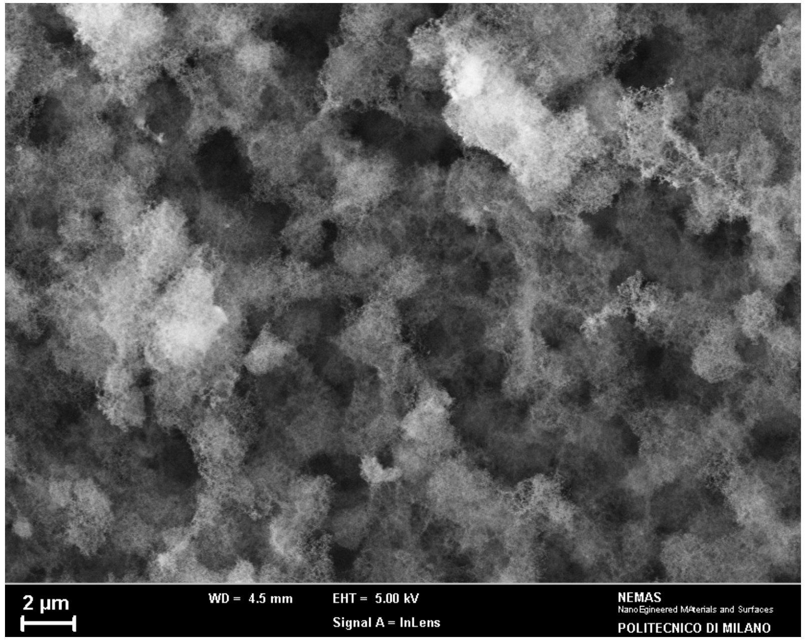

Multi-scale structure

Thickness: 1 to 100s µm
Area: from 1 mm^2 to 10 cm^2
Virtually any kind of substrate

A. Zani et al., *Carbon*. **56**: (2013) 358–365
A. Maffini et al., *Physical Review Materials* **3** (2019) 083404
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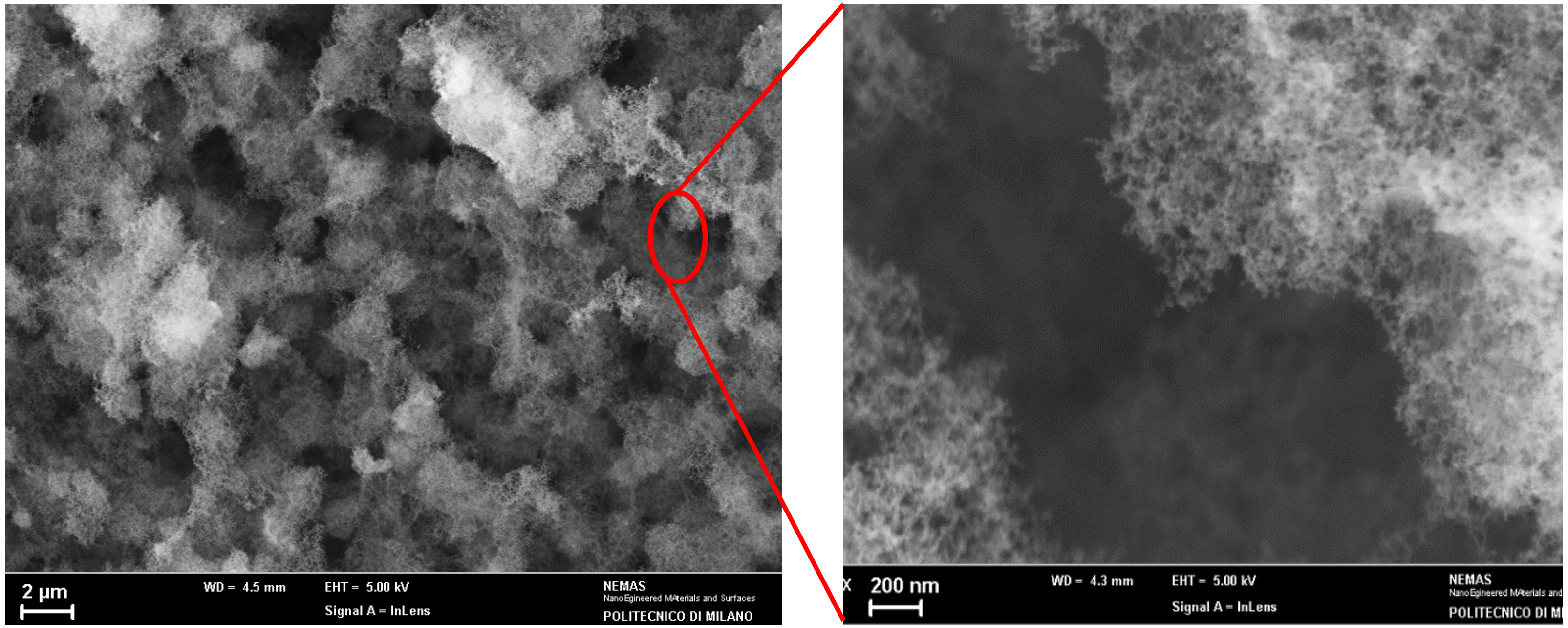

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Fractal-like aggregates

Gyration radius (R_g) ~ 0.1 – 5 μm
Fractal dimension (D) ~ 1.8 – 2.2

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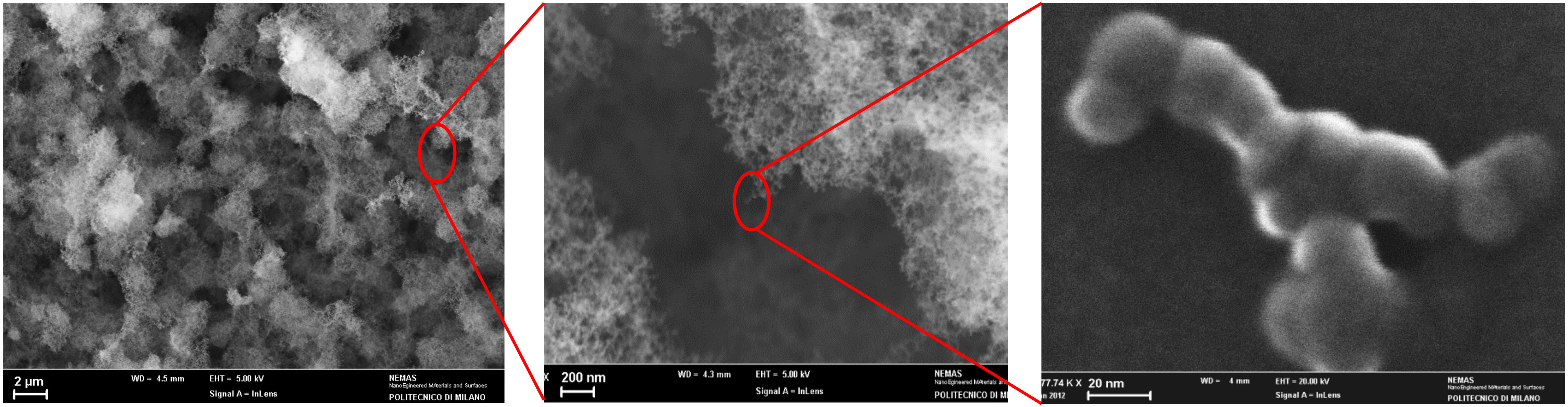

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Nanoparticle constituents:

NP radius (R_{np}) ~ 5 – 20 nm

NP density (ρ_{np}) ~ 50% – 100% of bulk

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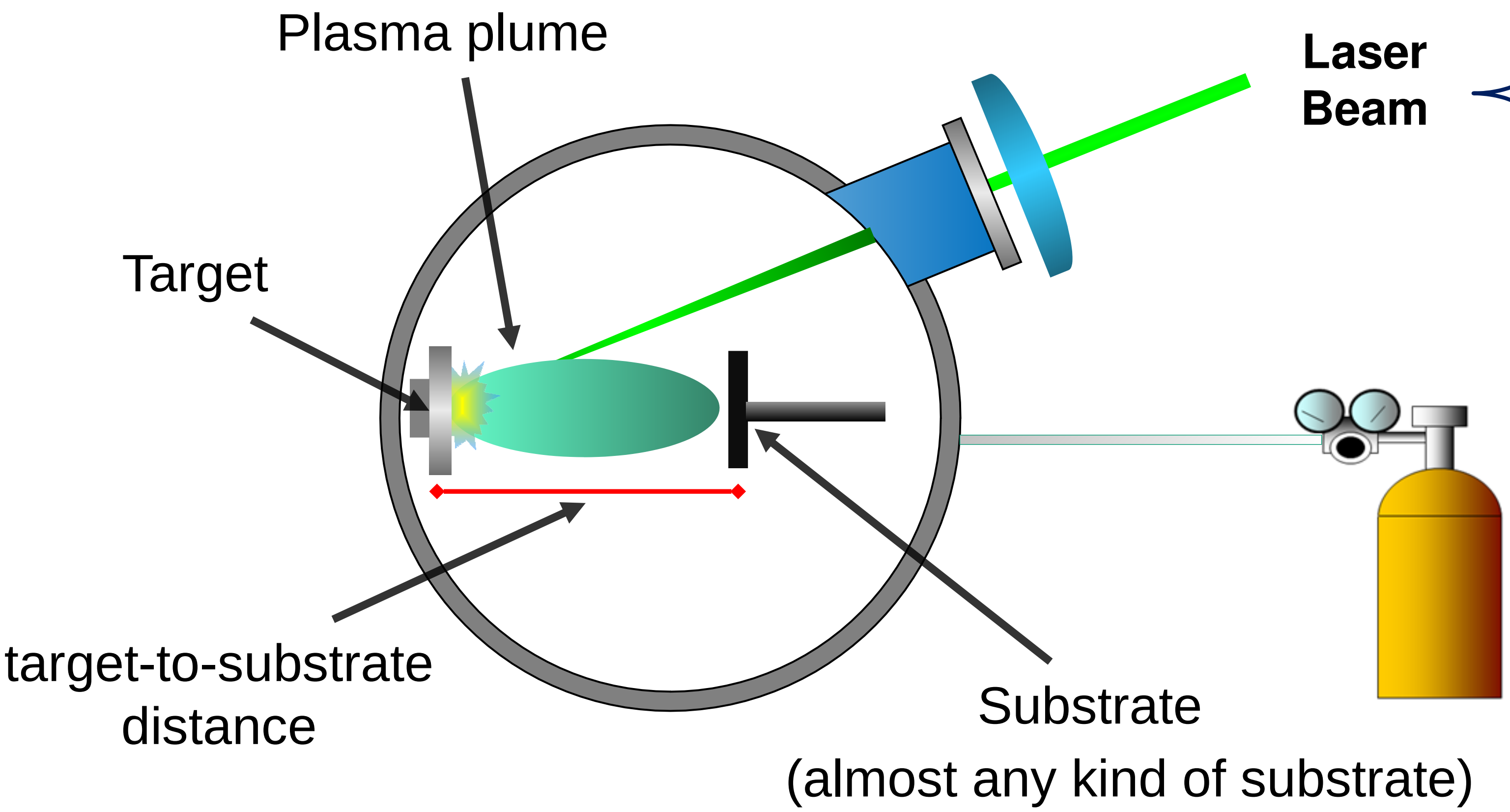
Pulsed Laser Deposition



Conventional ns-PLD:
~ 5 ns pulse duration
~ 1 J pulse energy

Alternative fs-PLD:
~ 100 fs pulse duration
~ 5 mJ pulse energy

Background Gas

- Inert (He, Ar..)
- Reactive (O_2)

A. Maffini et al., in *Nanoporous Carbons for Soft and Flexible Energy Devices*, Springer, 2022

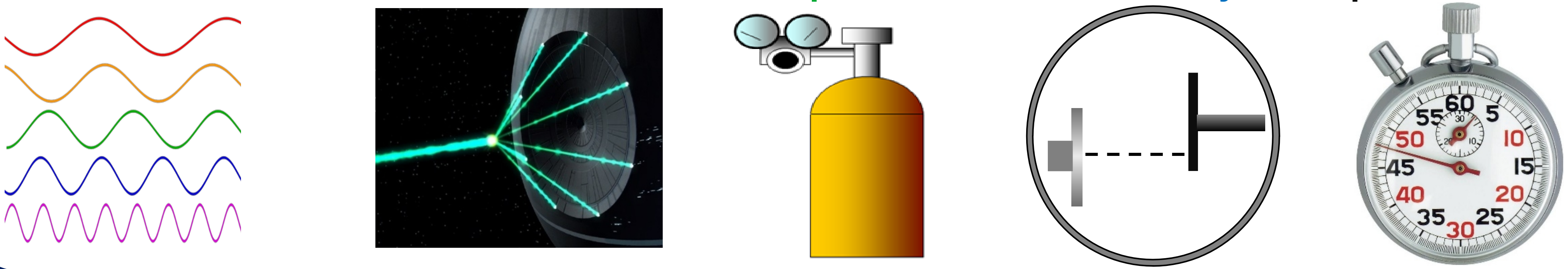
Foam properties control

Nano-scale
- Crystalline structure & composition
- Nanoparticle size

Micro-scale
- Aggregate size
- Morphology

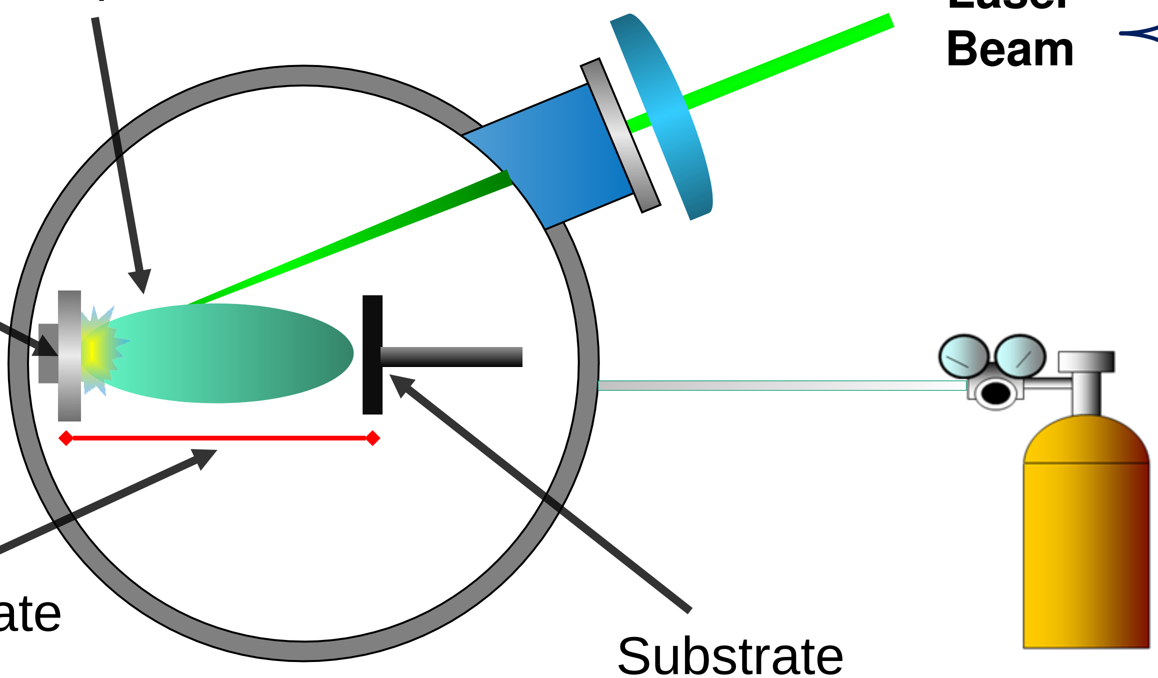
Macro-scale
- Uniformity
- Thickness profile

Pulse Duration **Laser Fluence** **Gas pressure** **Geometry** **Deposition time**



PLD process parameters

Pulsed Laser Deposition



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Unparalleled versatility

Complex, non-linear process

A. Maffini et al., in *Nanoporous Carbons for Soft and Flexible Energy Devices*, Springer, 2022

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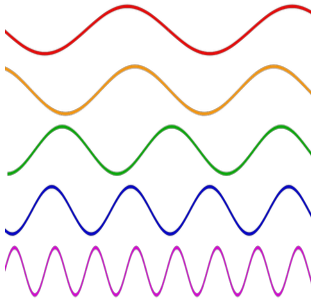
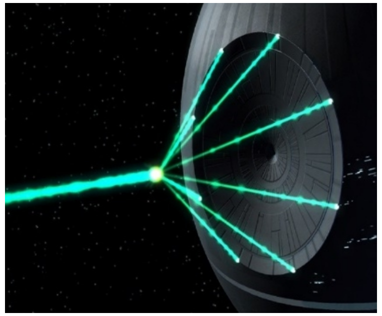
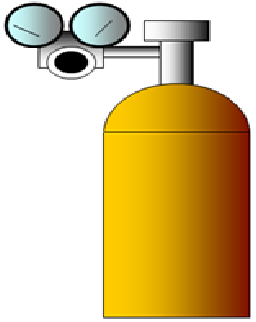


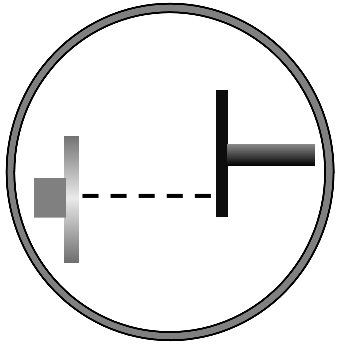
Laser Fluence



Gas pressure



Geometry



Deposition time

PLD process parameters

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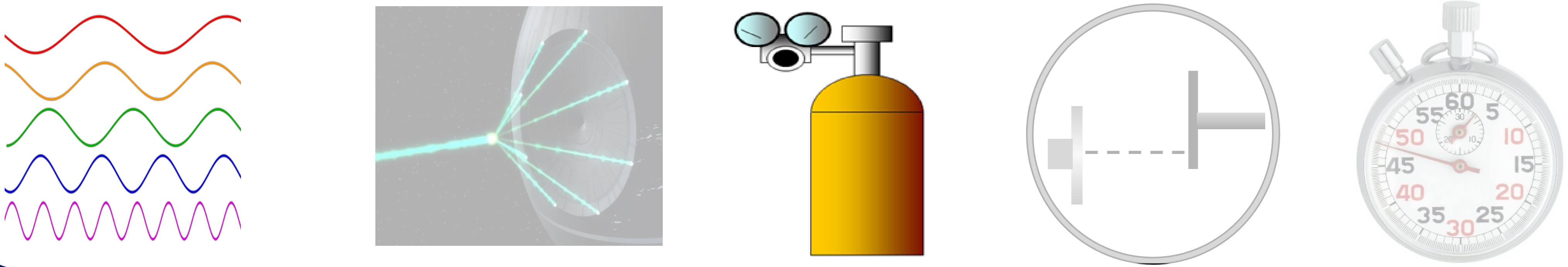
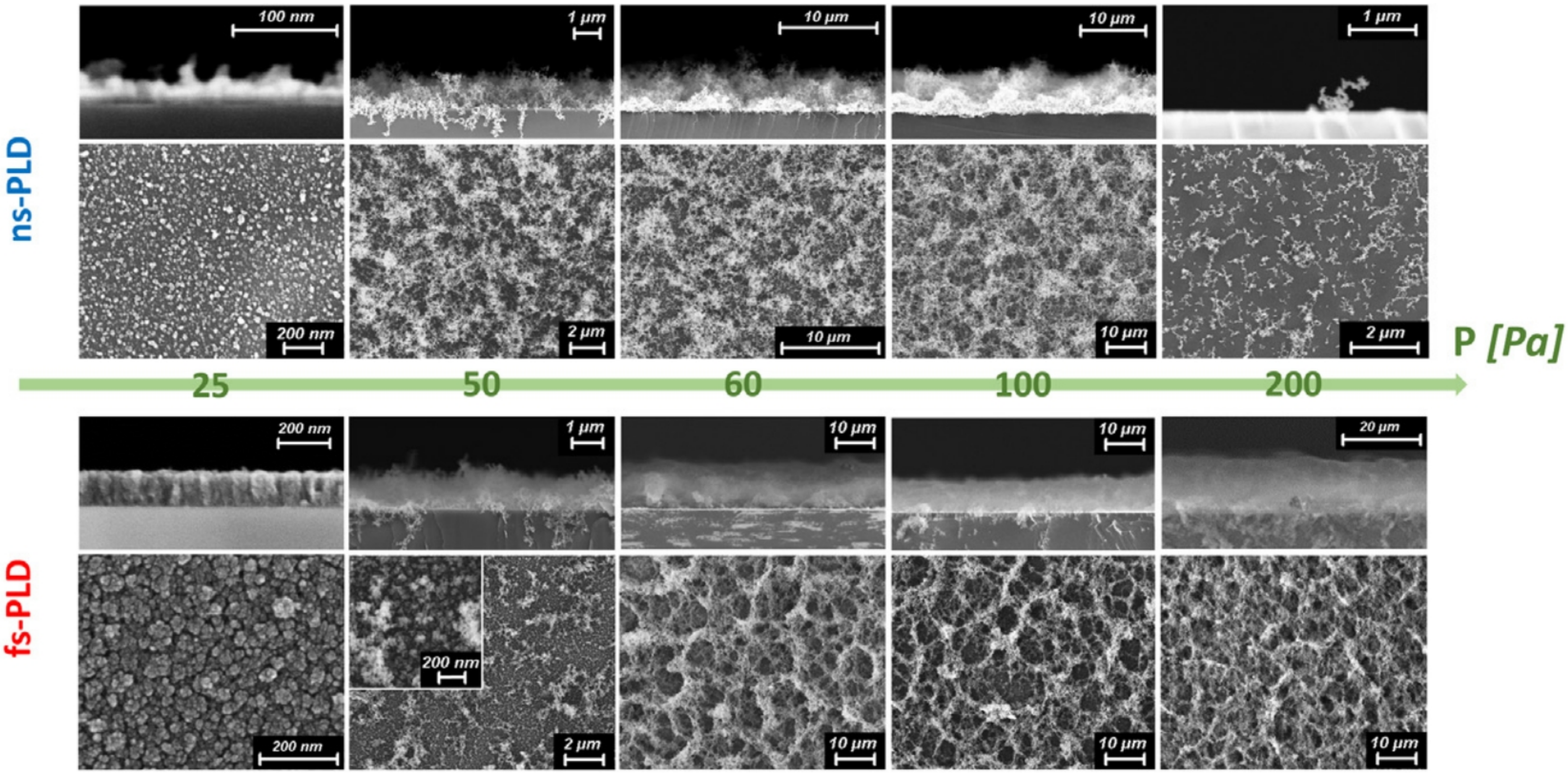
Pulse Duration | **Laser Fluence** | **Gas pressure** | **Geometry** | **Deposition time**



PLD process parameters

Example: the role of deposition pressure

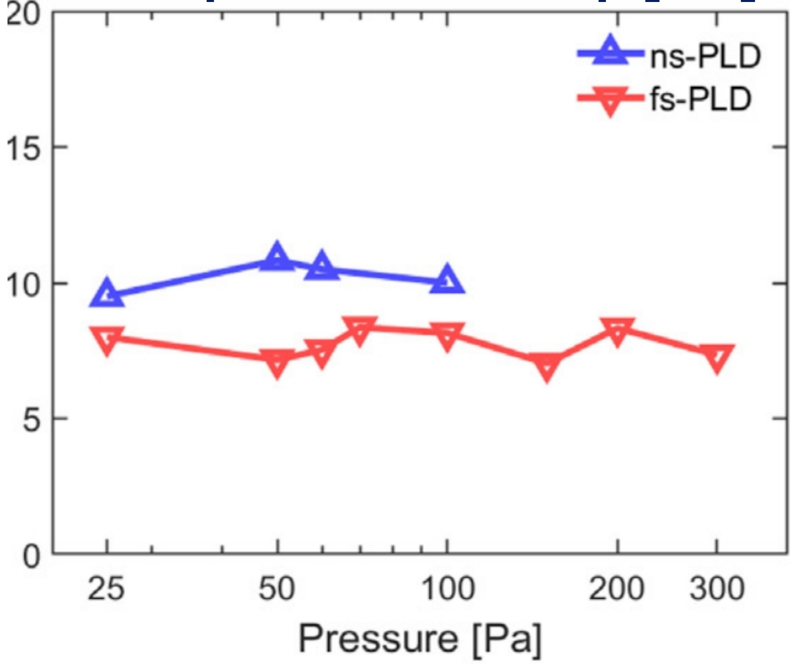


A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

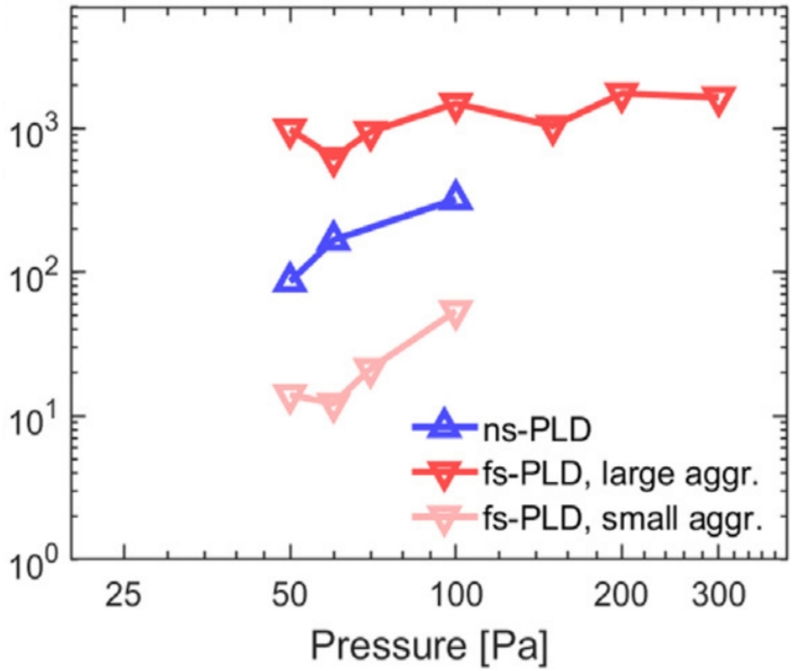
Talk by **D. Orecchia**, GS_11, Friday 8th Sept.

Nanofoam analysis at nano- and micro-scale

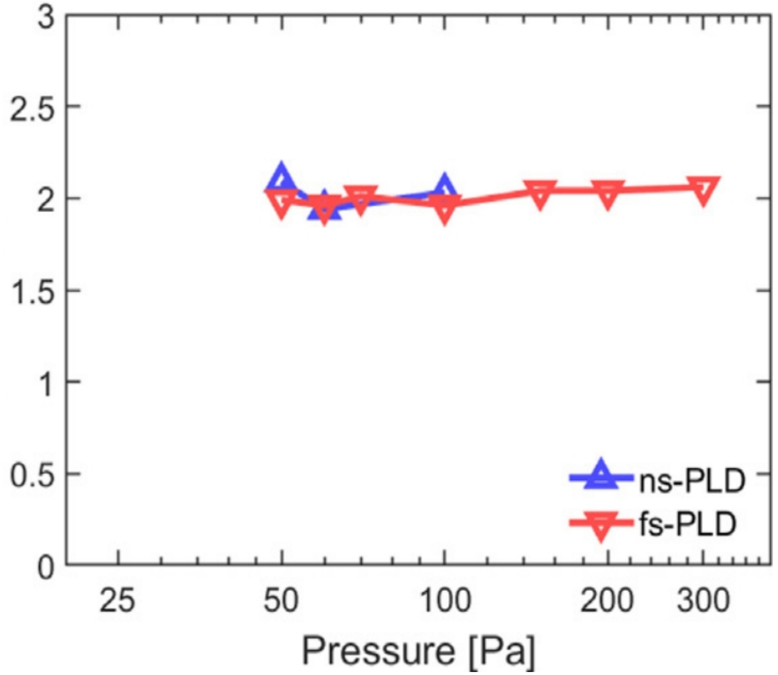
Nanoparticle size Rnp [nm]



Aggregate radius Rg [μm]



Fractal dimension D



Fractal scaling for density esitimation

$$\rho_f \approx \rho_{np}\, k \left(\frac{R_{np}}{R_g}\right)^{3-D}$$

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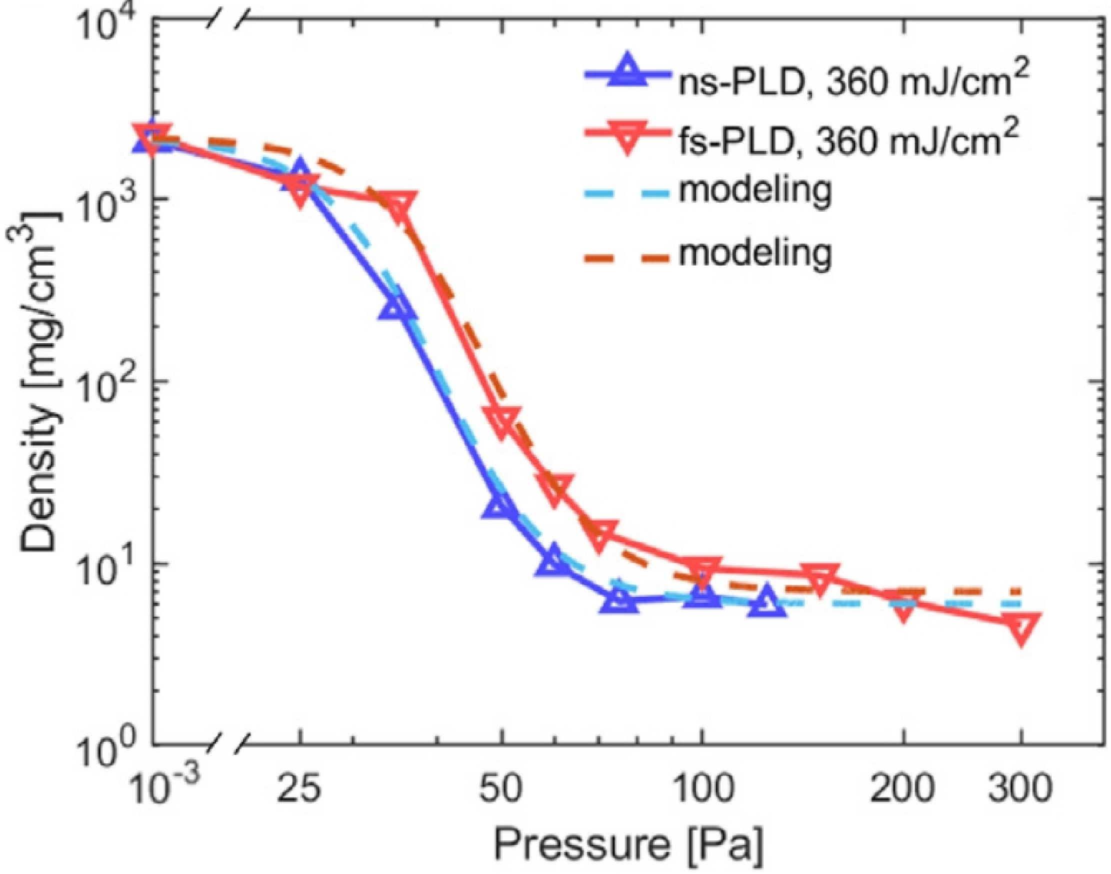
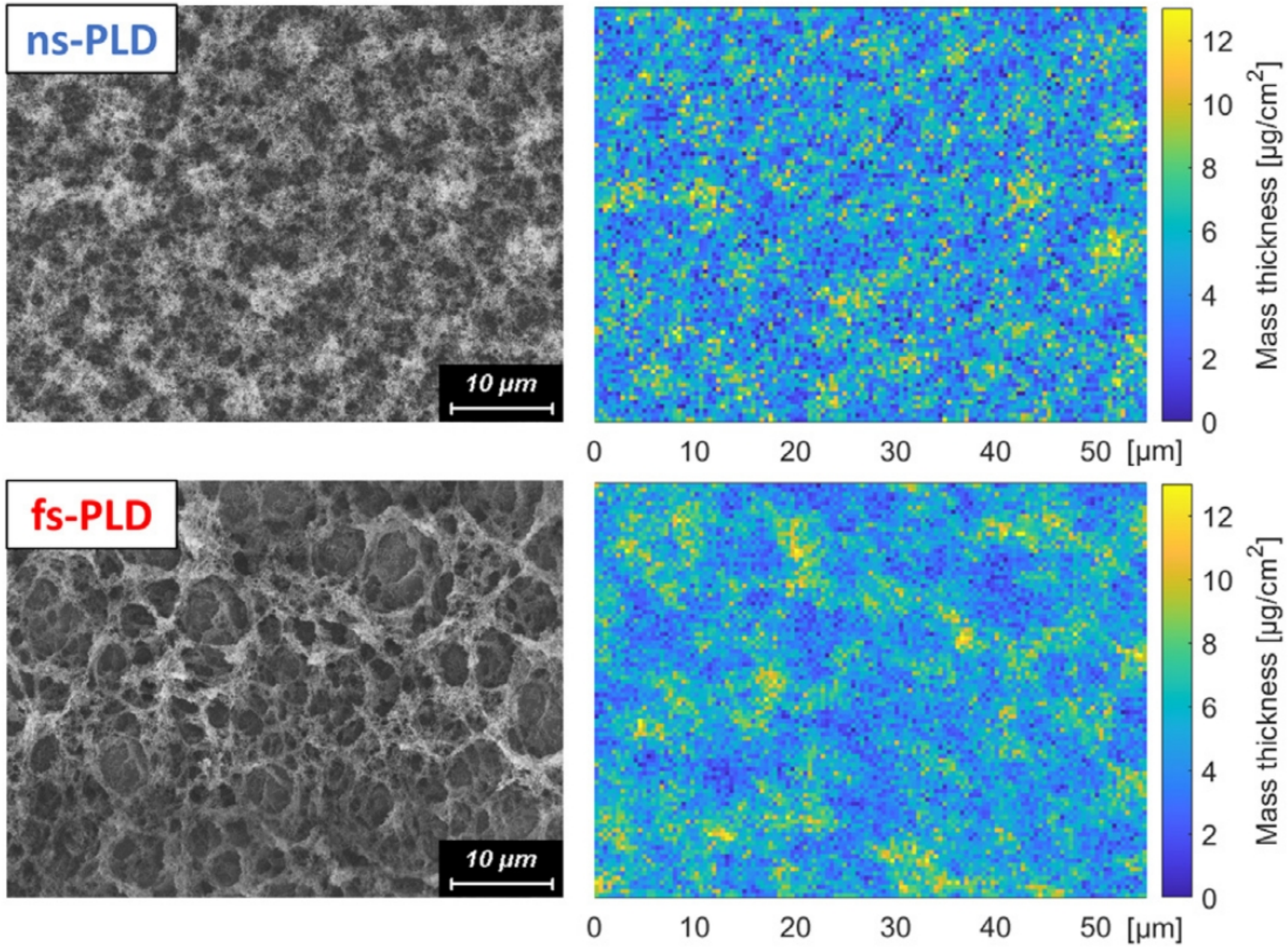
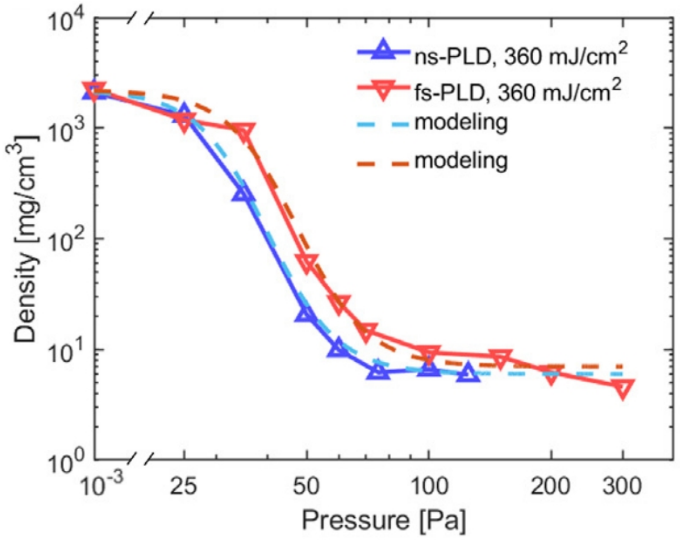
Fine tuning of nanofoam density and morphology

Carbon nanofoam density
[experiments and model]





A. Pazzaglia et al., *Material Characterization* **153** (2019) 92-102
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*



Functionally graded nanofoams

~ 300 Pa Ar

~ 30 Pa Ar

PLD Pressure (Ar)

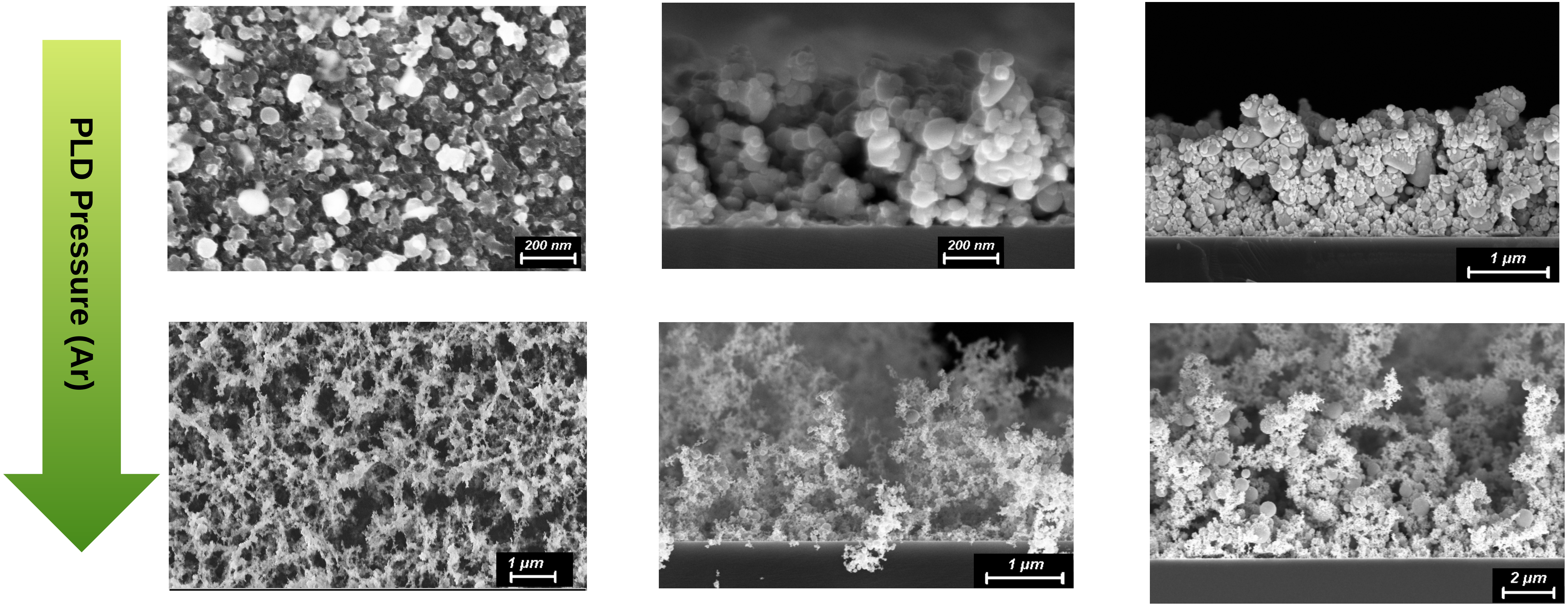
Density [mg/cm^3]

~10 mg/cm^3

~150 mg/cm^3

PLD nanofoams of many elements...

Boron | Titanium | Gold



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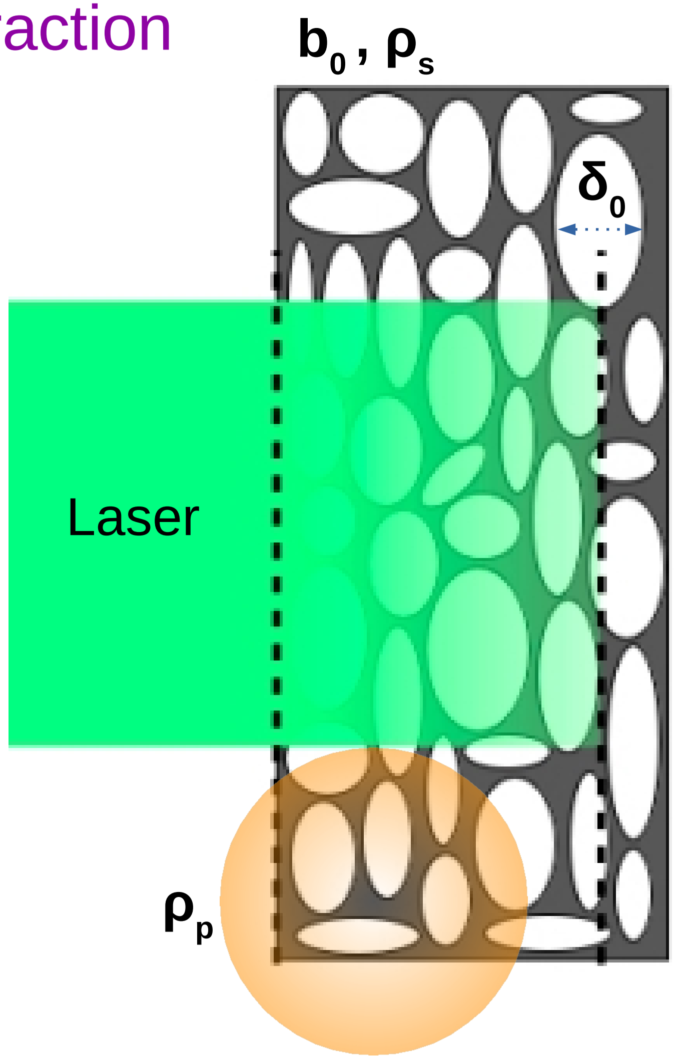
MULTI-FM: 1D hydrodynamic code to study laser-foam interaction

Laser-plasma dynamics in an "effective medium" with fills and gaps.



M. Cipriani et al., Laser and Particle Beams, **36** (2018) 121-128

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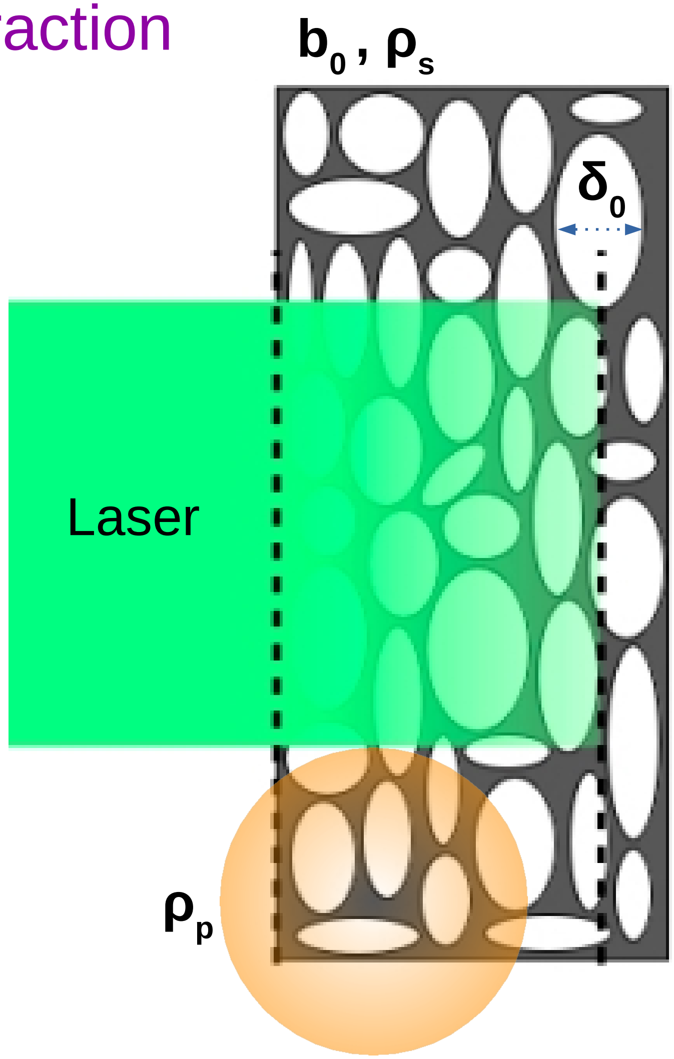
Main modeling parameter: **degree of plasma homogenization**

- Initial pore size= δ_0
- Initial solid element size=b_0
- Density of solid parts = ρ_s
- Foam fractal parameter = α
- Average plasma density ρ_p given by fractal scaling
- **Homogenization time=** $_H(b_0,\delta_0,\rho_p,\text{Temperature})$

$$\rho_p = \rho_s \left(\frac{b_0}{\delta_0}\right)^{\frac{1}{\alpha}}$$

Validated for conventional (micrometric, plastic) foams….



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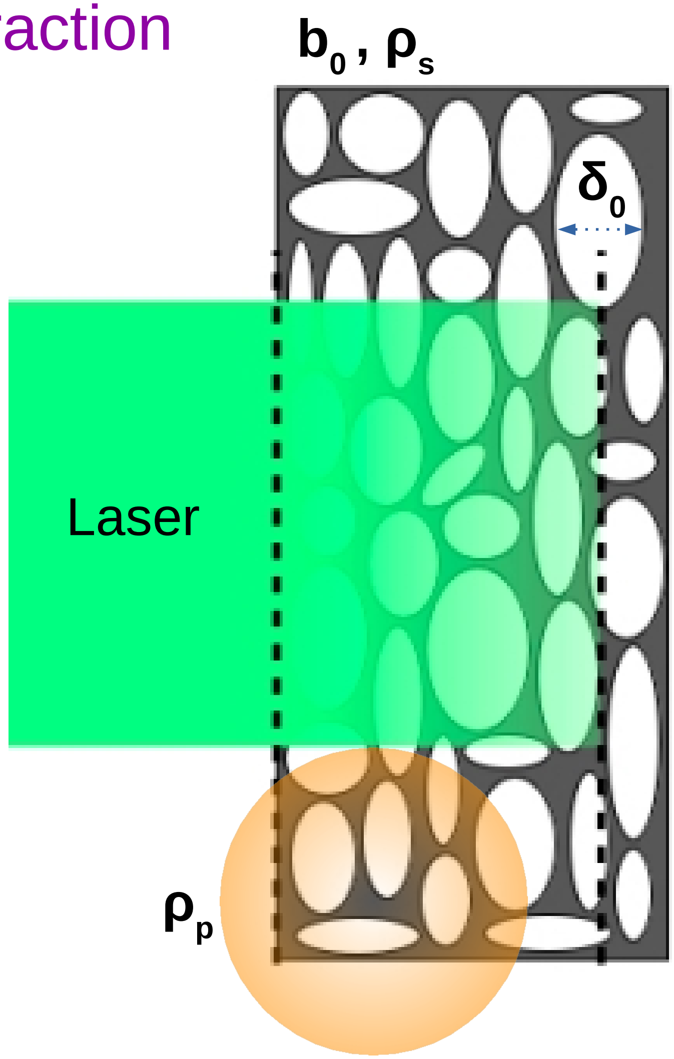
...application to carbon and nanofoams is a novelty!



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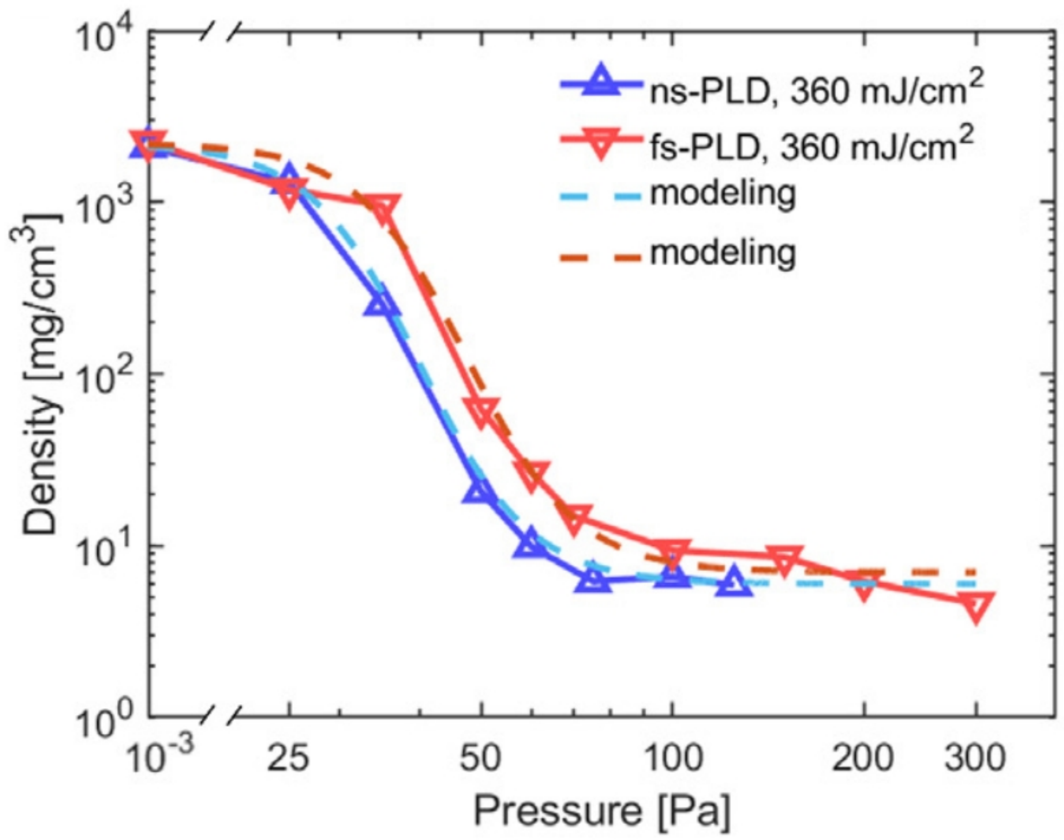
MULTI-FM simulation of nanofoam irradiation



A. Maffini et al., Laser and Particle Beams, **2023**, Article ID: 1214430

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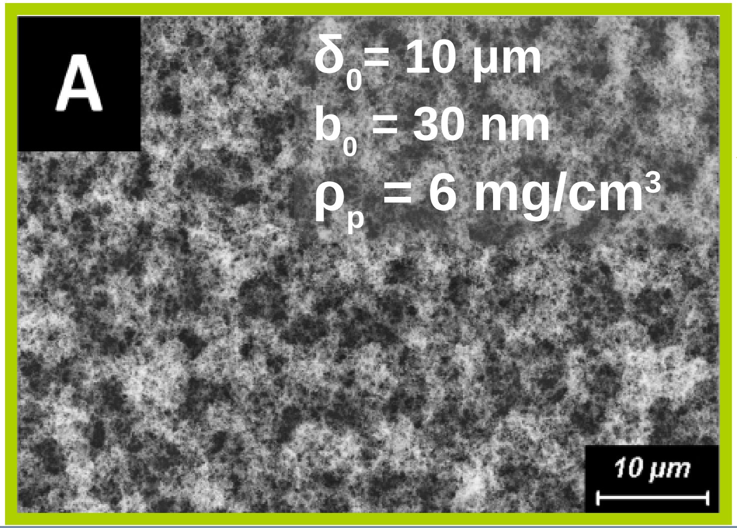

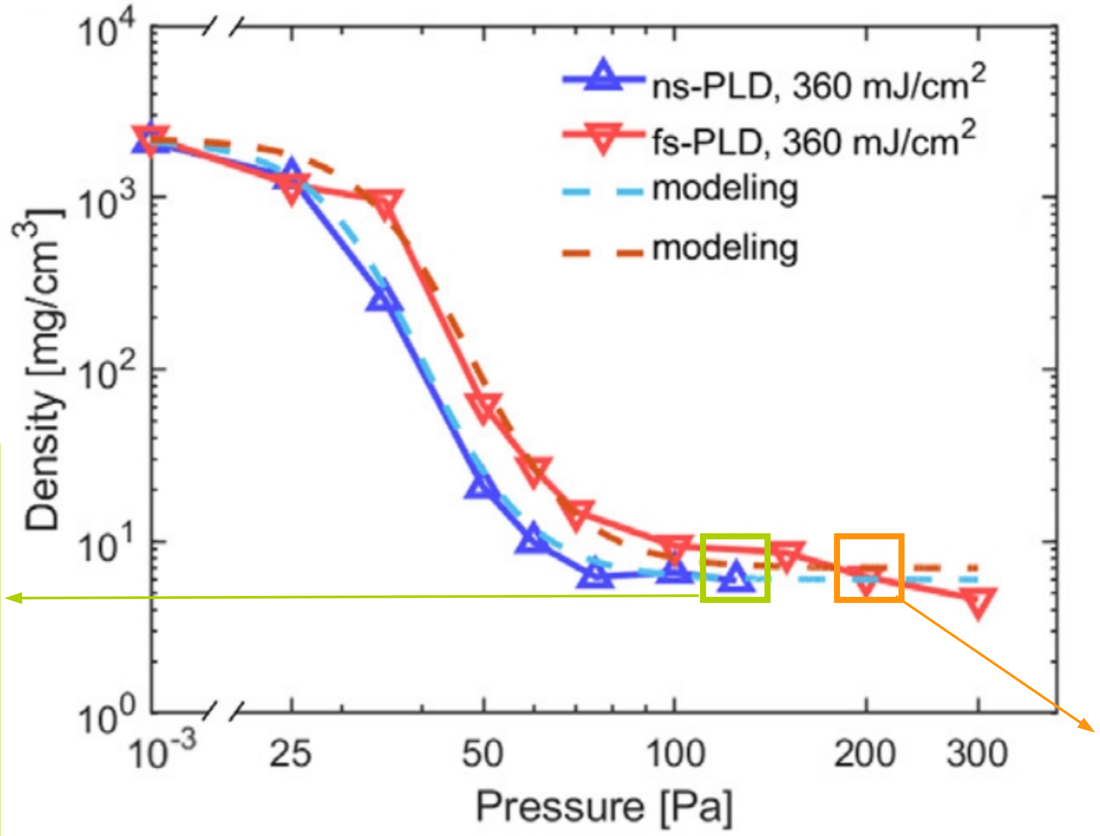

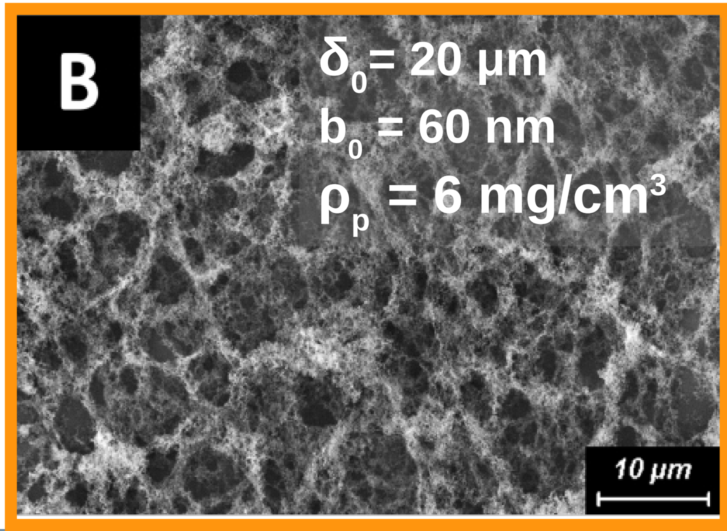

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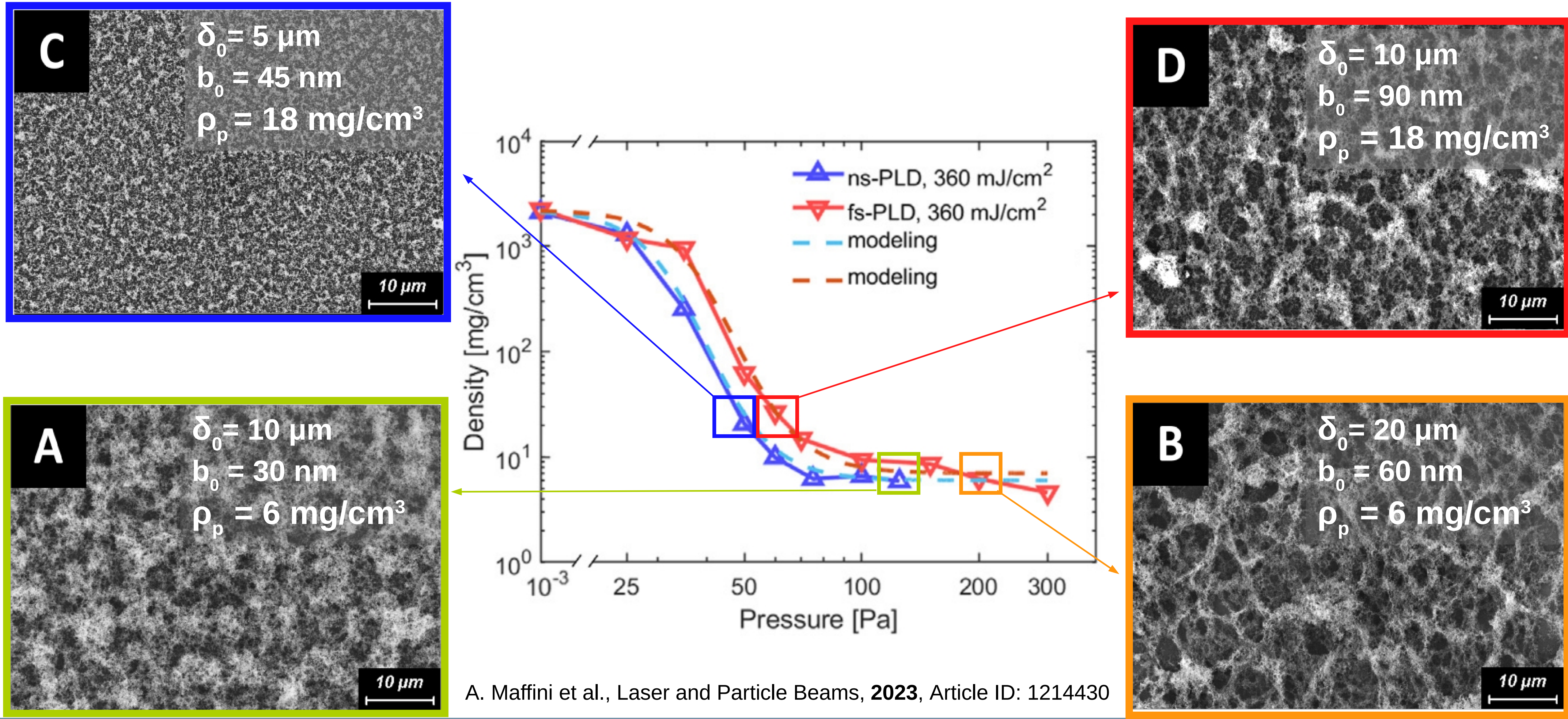

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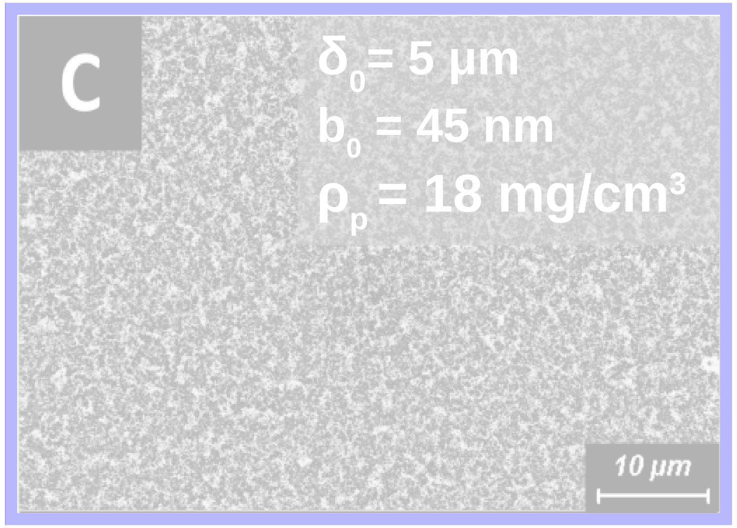
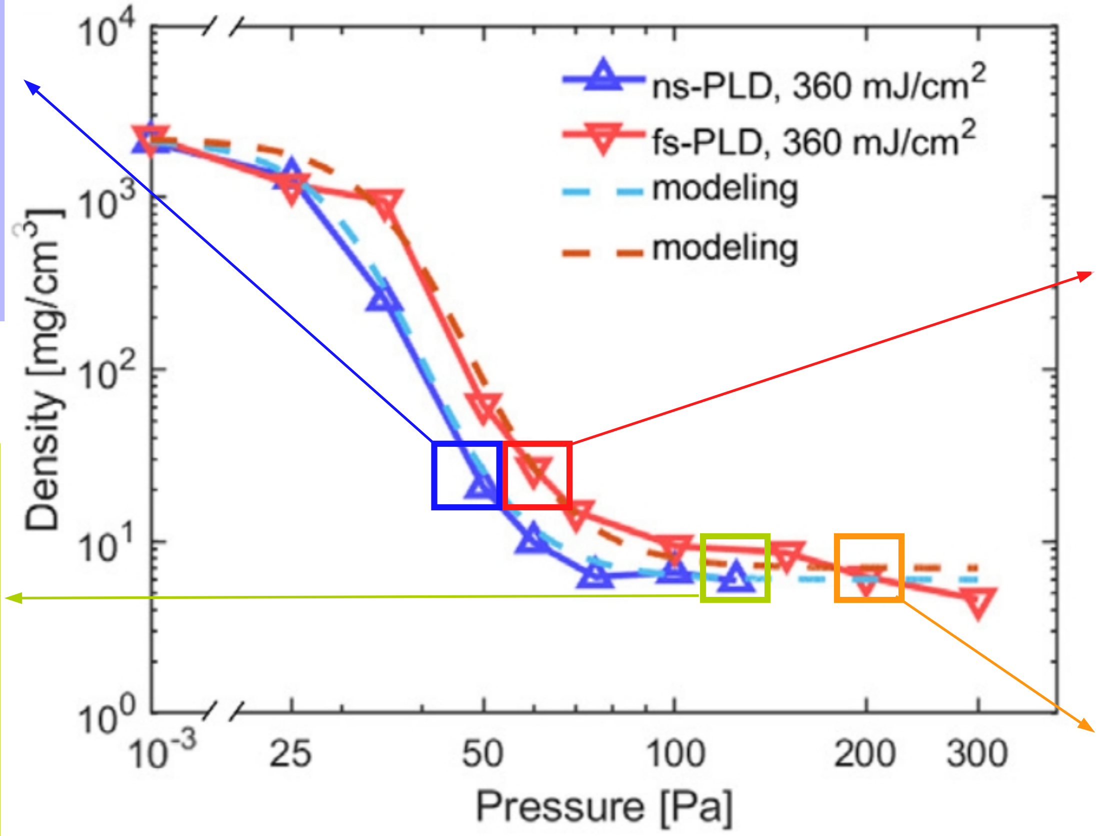
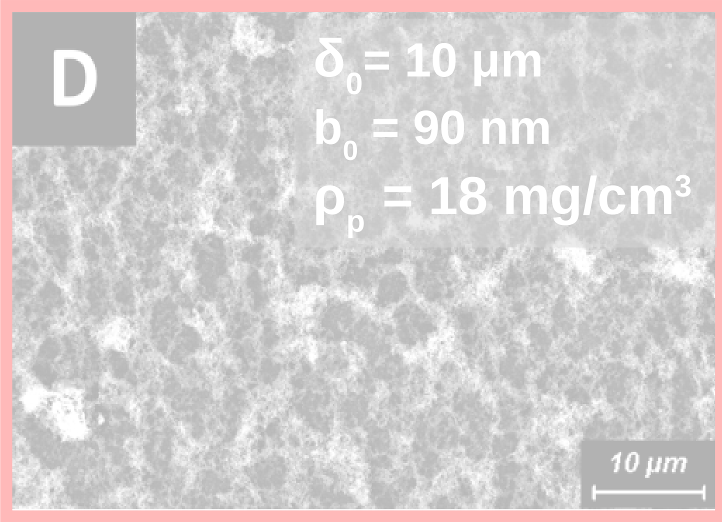
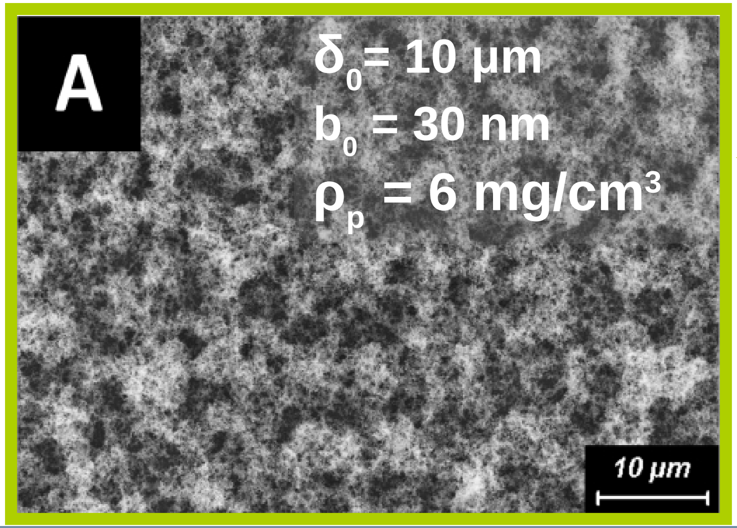
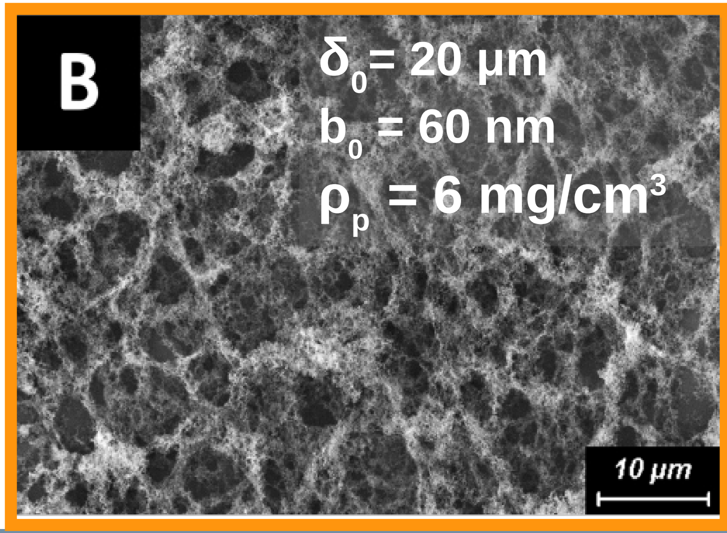








A. Maffini et al., Laser and Particle Beams, **2023**, Article ID: 1214430



MULTI-FM simulation of nanofoam irradiation

Laser parameters:

Wavelength = 1054 nm
Temporal FWHM = 3 ns
Intensity = 10^{14} W/cm^2

Same as **ABC** laser @ ENEA Frascati

Full ionization, $Z_{eff} = 6 \rightarrow n_c \sim 3.3$ mg/cm^3

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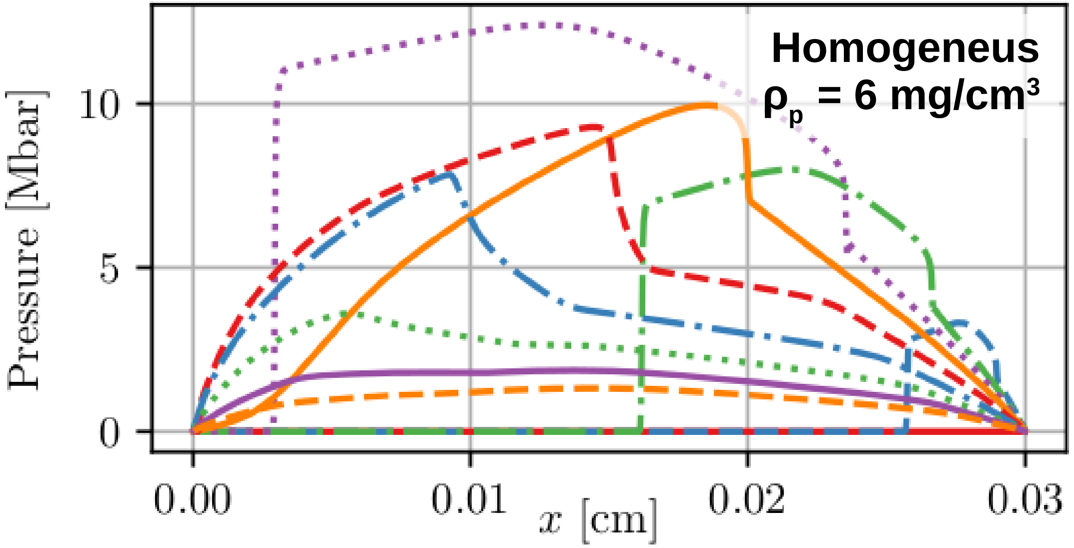

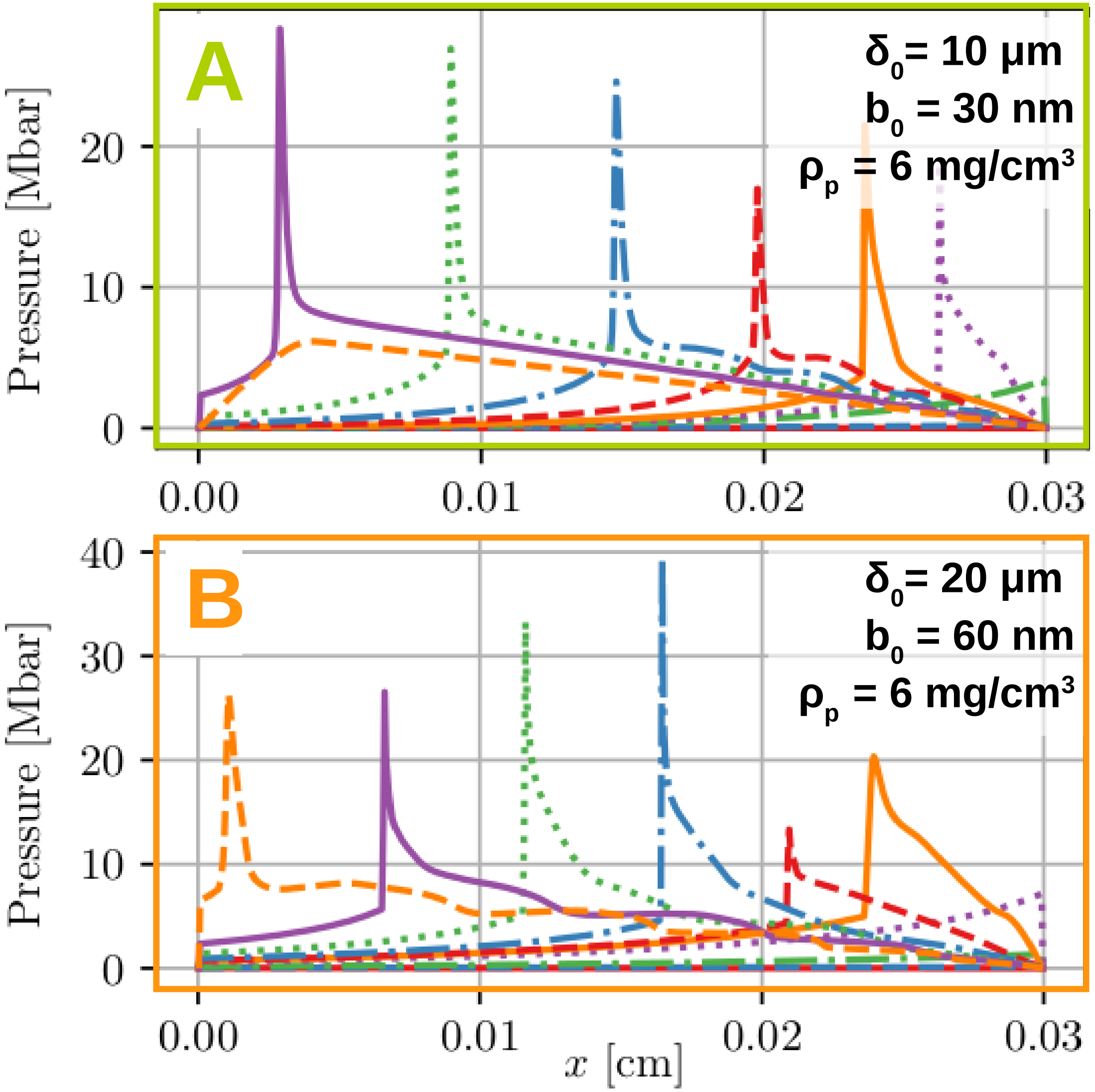

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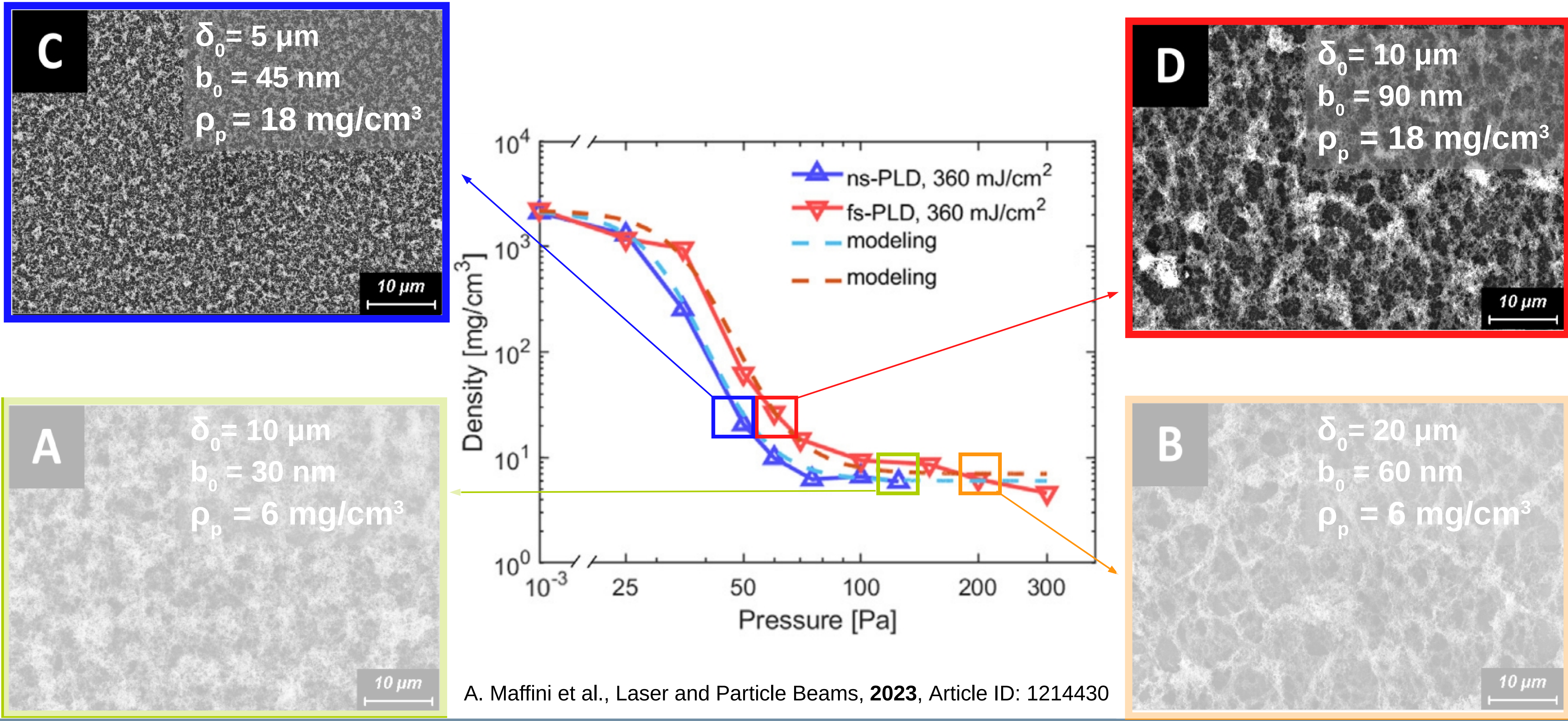

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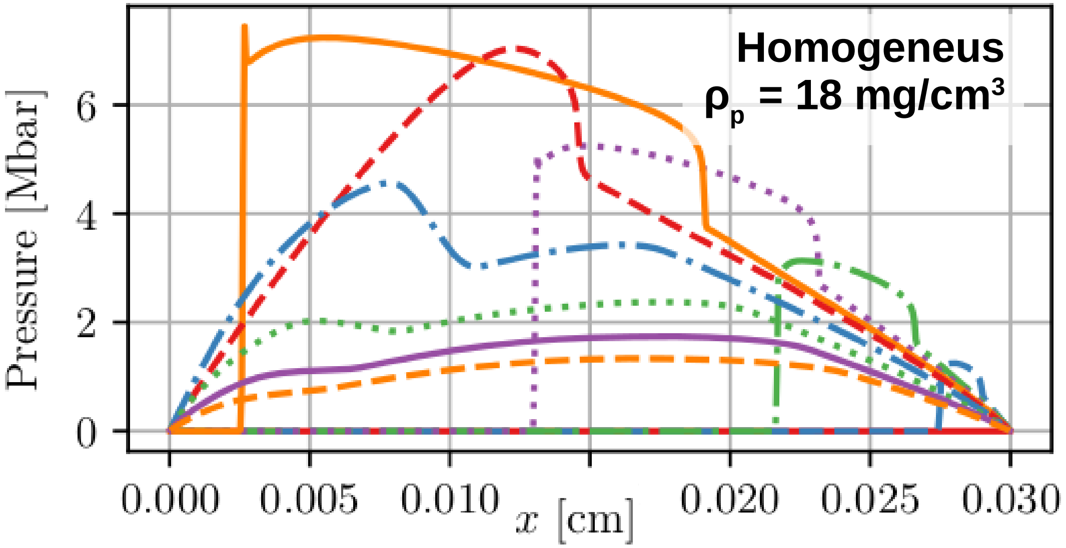
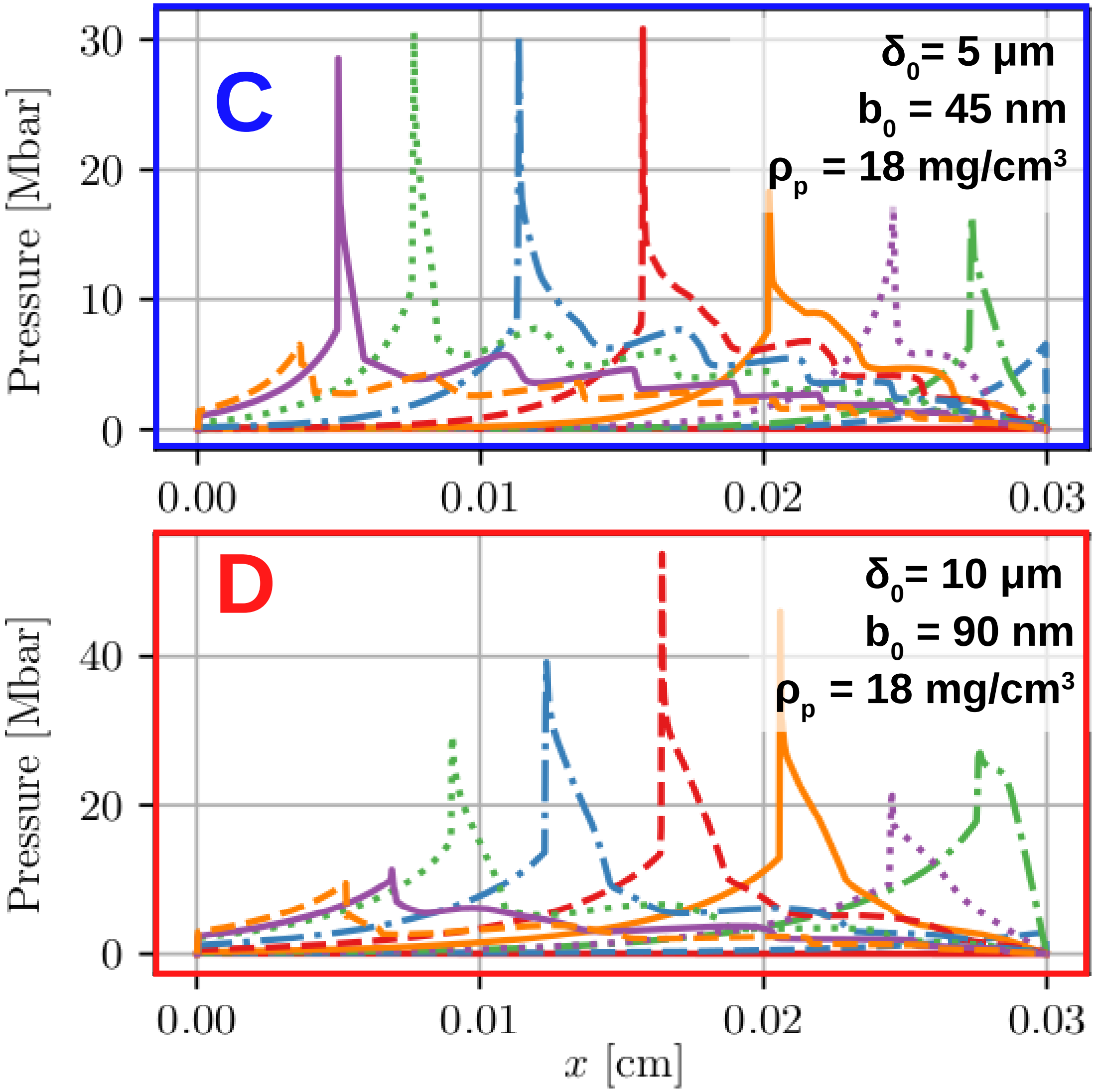
$\boldsymbol{\rho_p}$ **= 18 mg/cm**^{3}, different nanostructure





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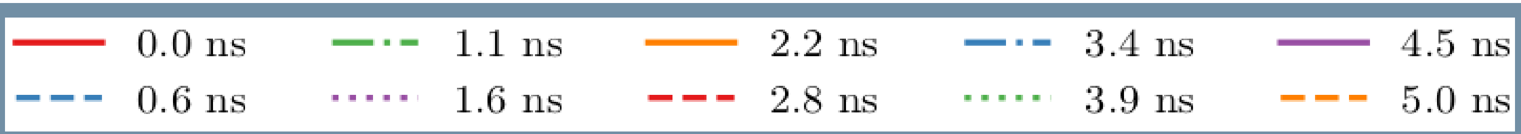

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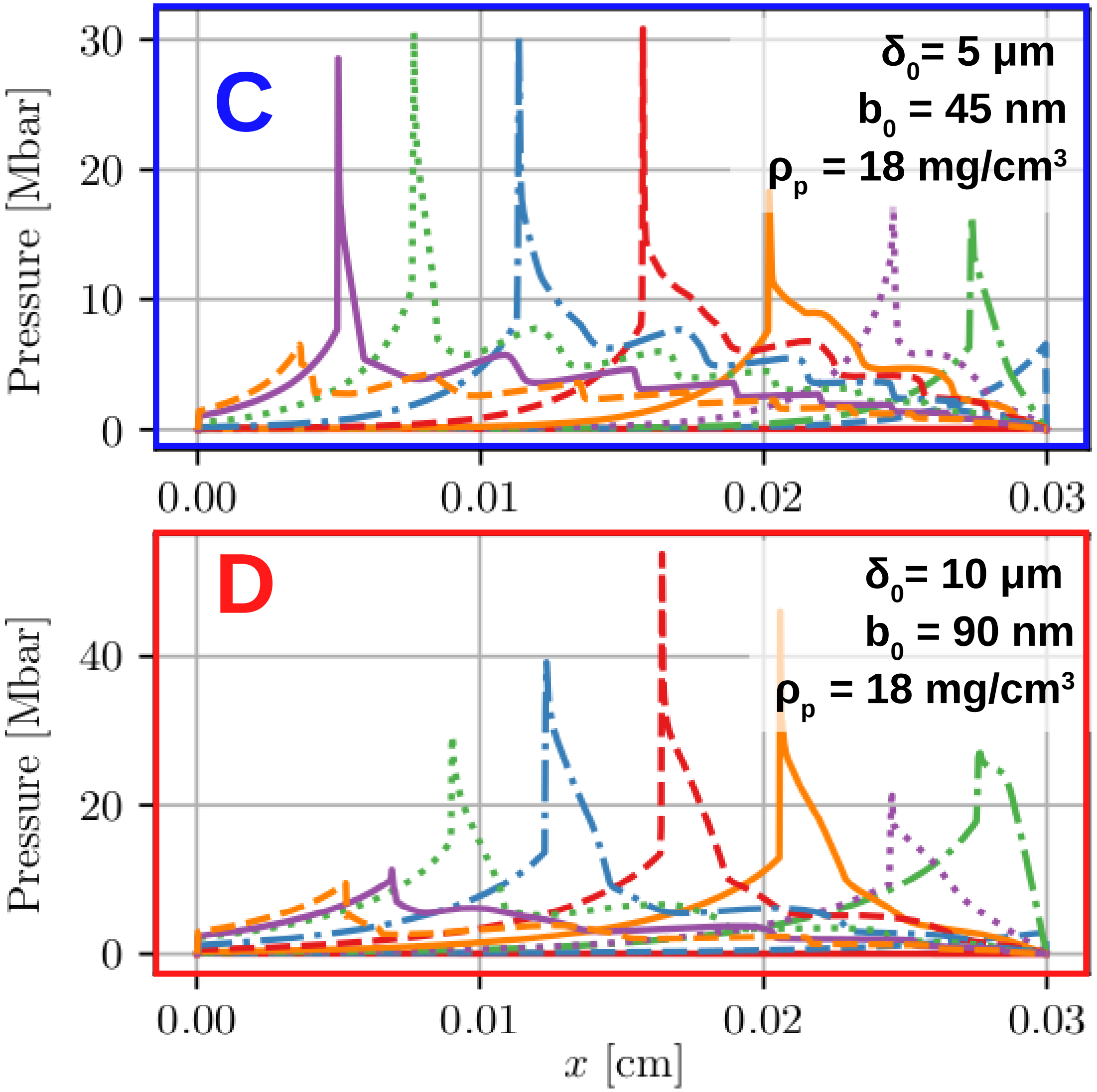

Main results:

- Pressure enhancement with nanostructure
- Higher ρ_p gives higher pressure
- At constant ρ_p , larger pores yield higher pressure
- Thickness > 100 μm is required
- Substrate effect not included
- Experimental validation is required

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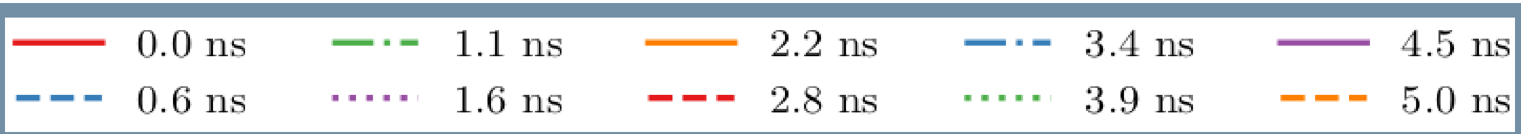

Carbon nanofoams irradiation @ ABC ENEA

Laser parameters

Wavelength = 1054 nm
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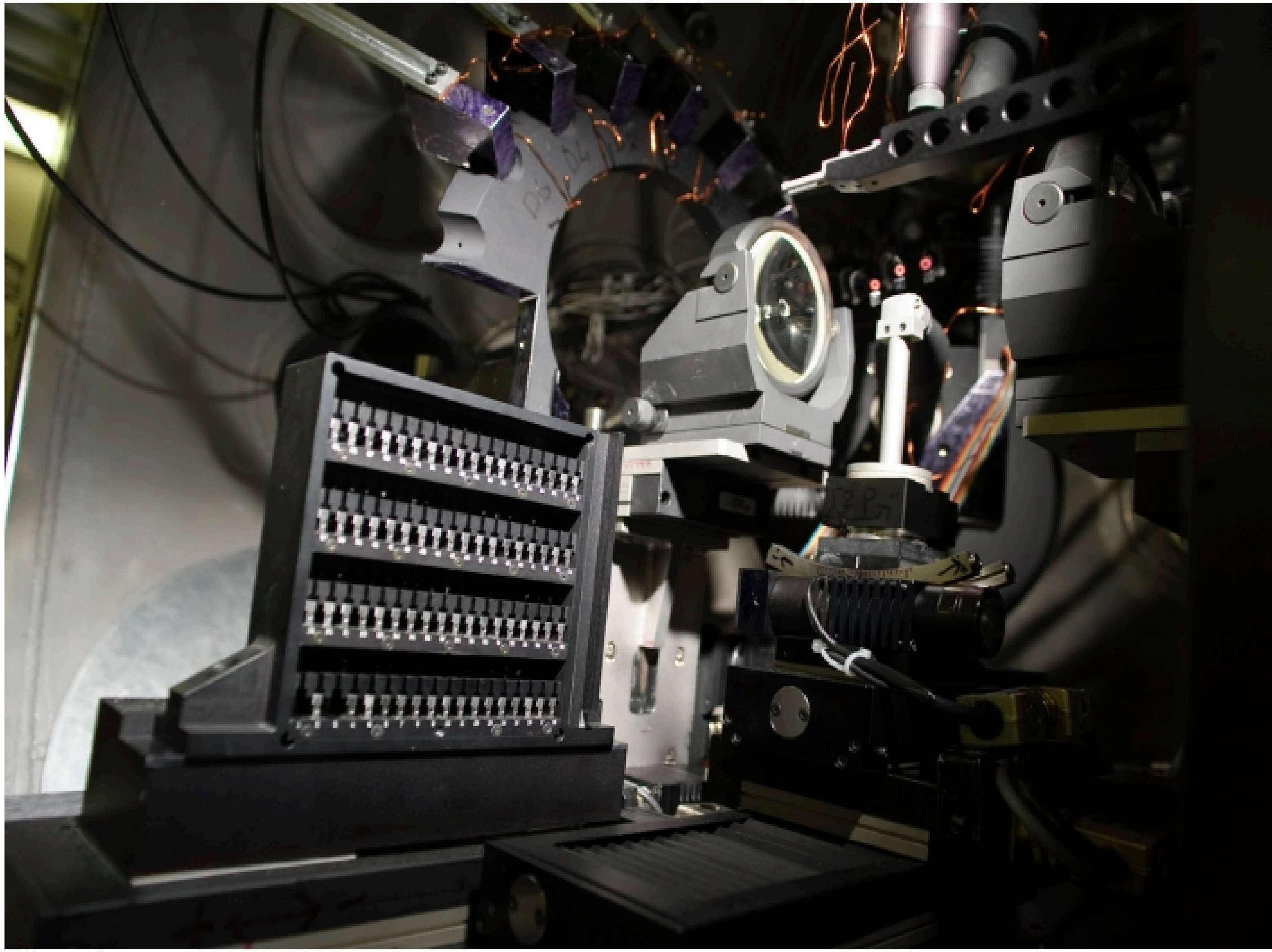
Target parameters

Substrates: 1.5 μm Al, bulk Al
Foam density: 6 mg/cm^3 , 26 mg/cm^3
Foam thickness: 30 μm to 270 μm



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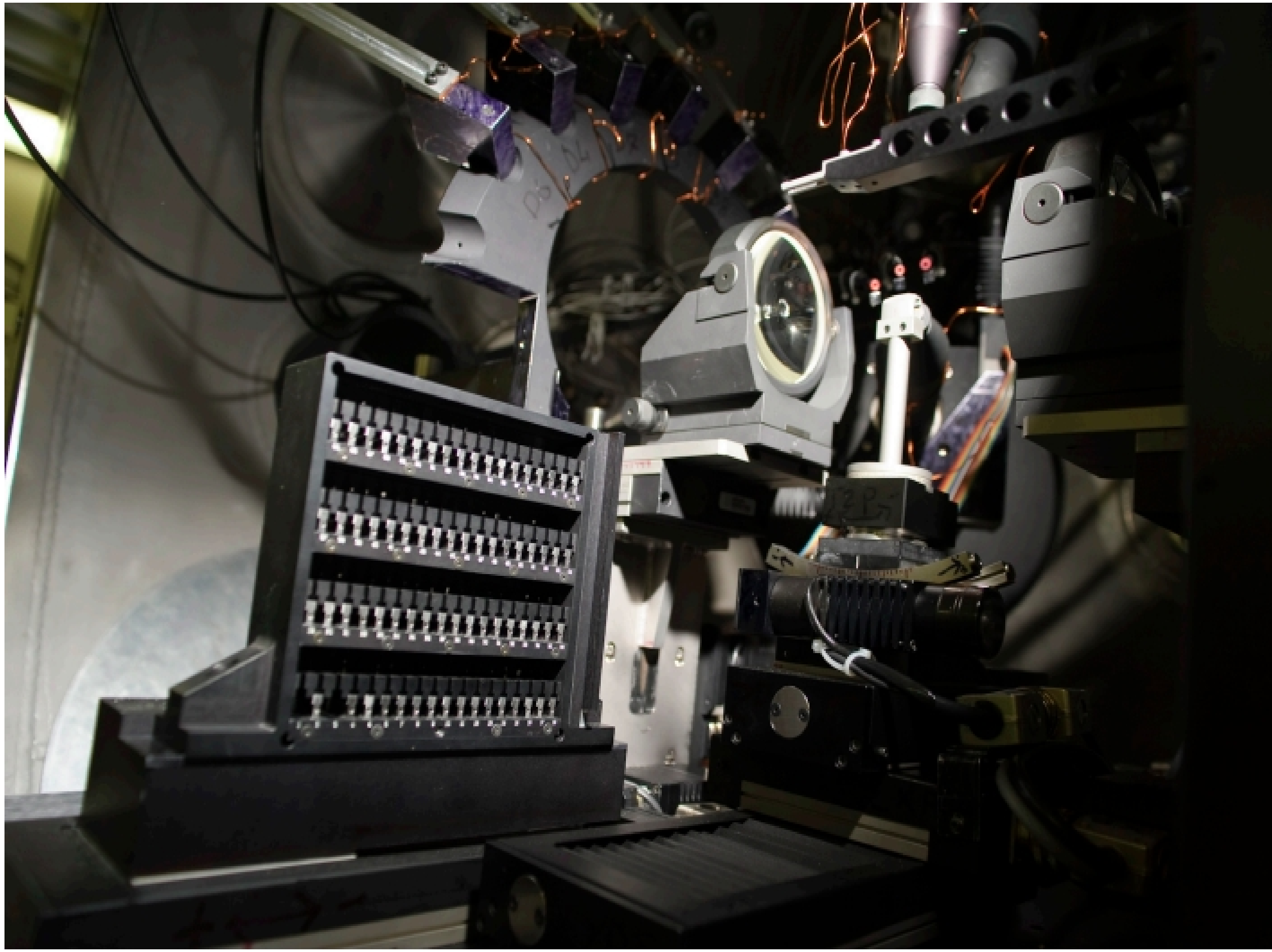
Optical emission & streak camera
Interferometry & shadowgraphy
Particle & x-ray emission
Post-mortem crater analysis



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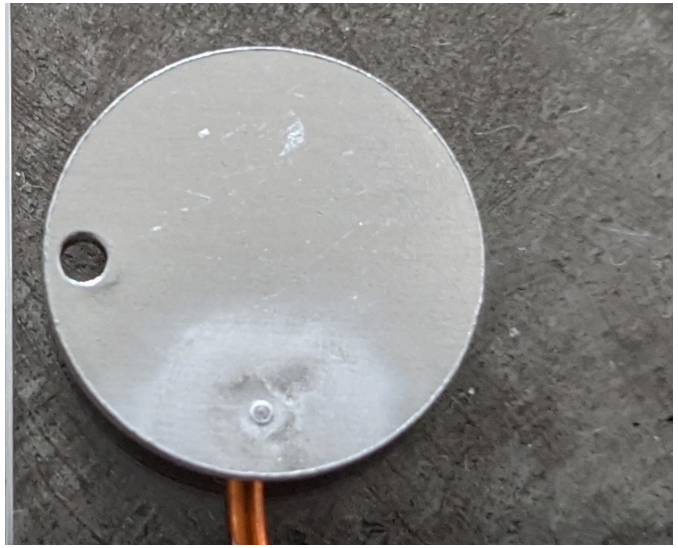
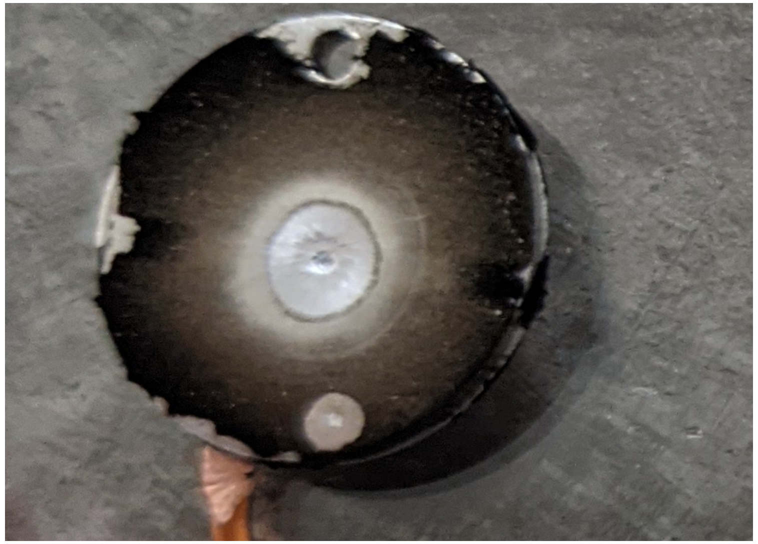
Analysis of laser-made craters

Bulk Al, **no foam**



Bulk Al + **foam 6 mg/cm^3**



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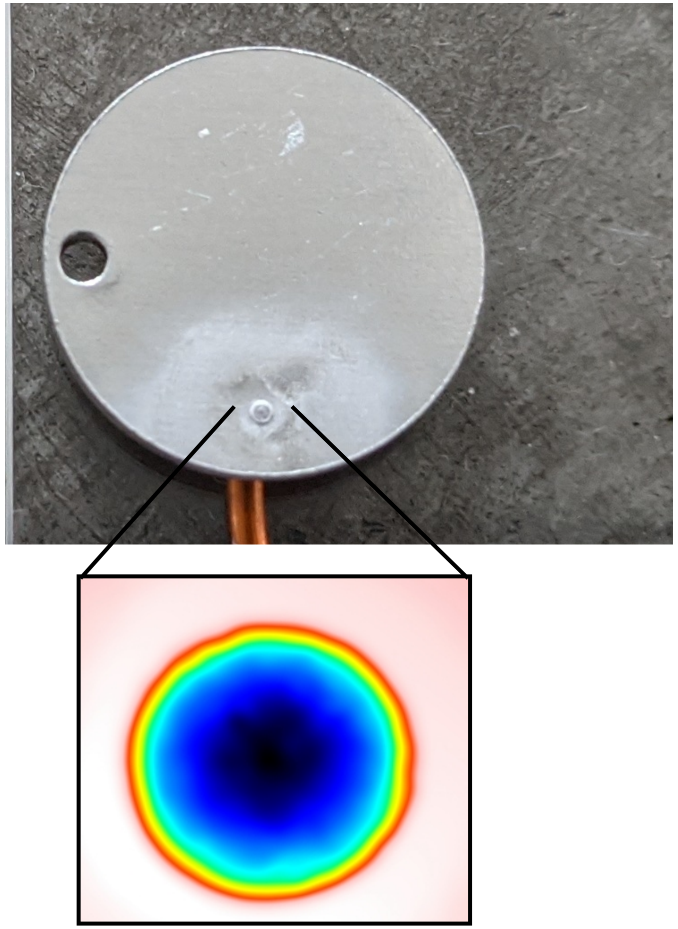
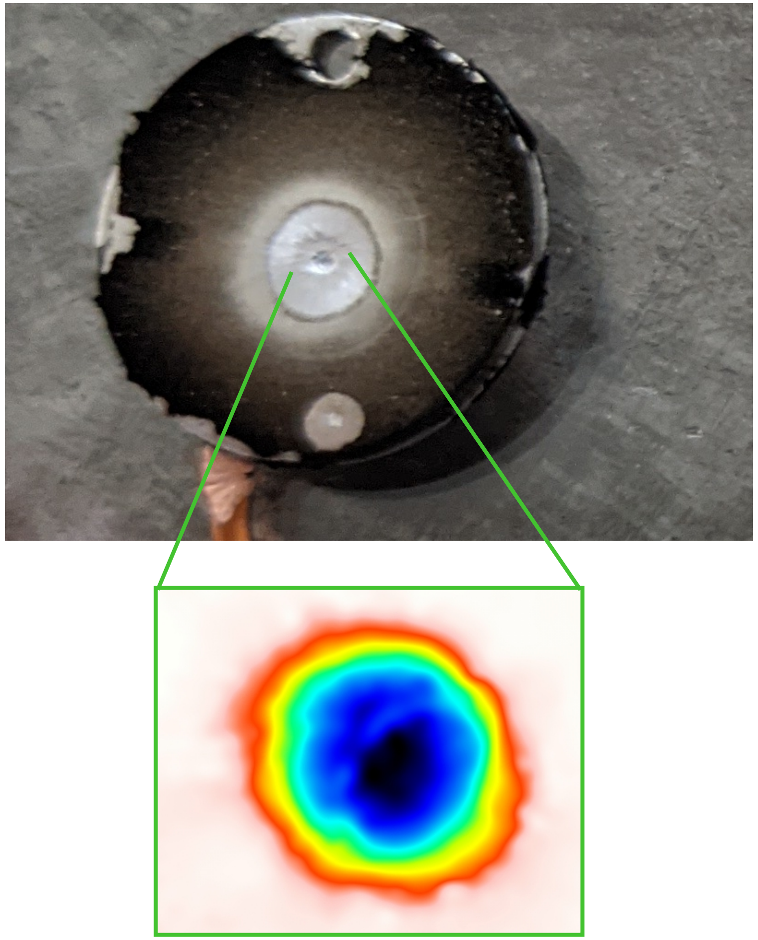


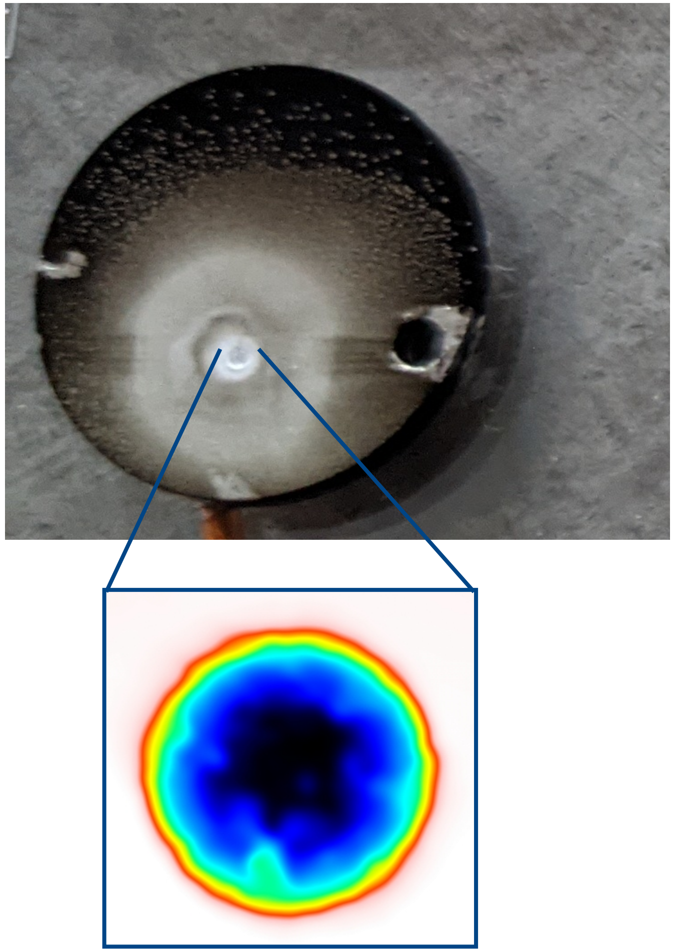
Volume ~ 3.5* 10^7 μm^3

Bulk Al + **foam 6 mg/cm³**



Volume ~ 4* 10^7 μm^3

Bulk Al + **foam 26 mg/cm³**



Volume ~ 6* 10^7 μm^3

Conclusions and perspectives

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- PLD nanofoams have **potential** application also **in ICF**
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Analysis of experimental data is ongoing

(*) Interferometria differenziale

Thank you for your attention!