Pulsed Laser Deposition of nanofoam targets for laser-driven inertial fusion experiments

A. Maffini, D. Orecchia, A. Formenti, V. Ciardiello , M. Cipriani , F. Consoli , M. Passoni

ECLIM 2022
36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Frascati, 21/9/2022

EUROfusion

Why foam targets in laser-matter interaction?

Why Pulsed Laser Deposition of nanofoams?

Features of PLD nanofoams

PLD nanofoam in laser-matter interaction & ICF

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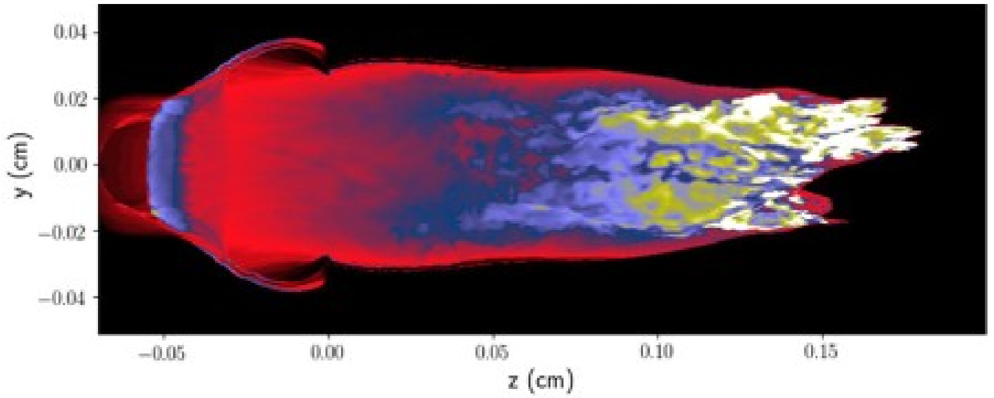
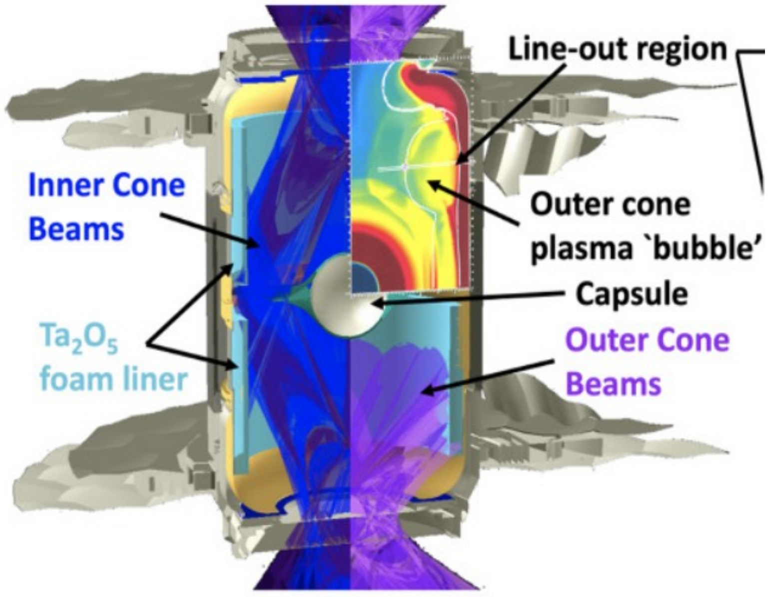
Why foams for laser-matter interaction?

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



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



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

- ✅ Bright x-ray sources (e.g. in hohlraum internal walls)
- ✅ Increased laser conversion into particle energy

O-4 J. Limpouch
O-7 S. Shekhanov
O-8 L. Hudec
I-8 O. Rosmej
… and many more!

Conventional foams for laser-plasma experiments

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

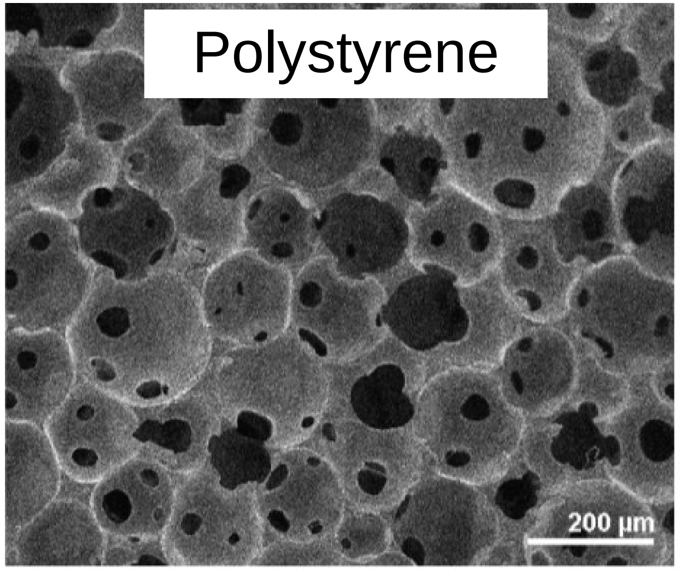
Cite as: Phys. Plasmas **25**, 030501 (2018); https://doi.org/10.1063/1.5009689
Submitted: 19 October 2017 • Accepted: 20 February 2018 • Published Online: 16 March 2018

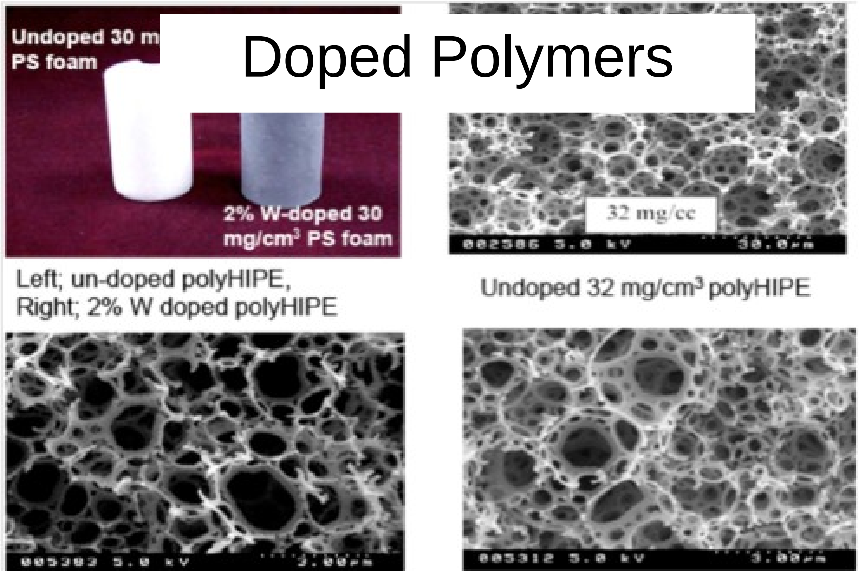
Keiji Nagai, Christopher S. A. Musgrave and Wigen Nazarov

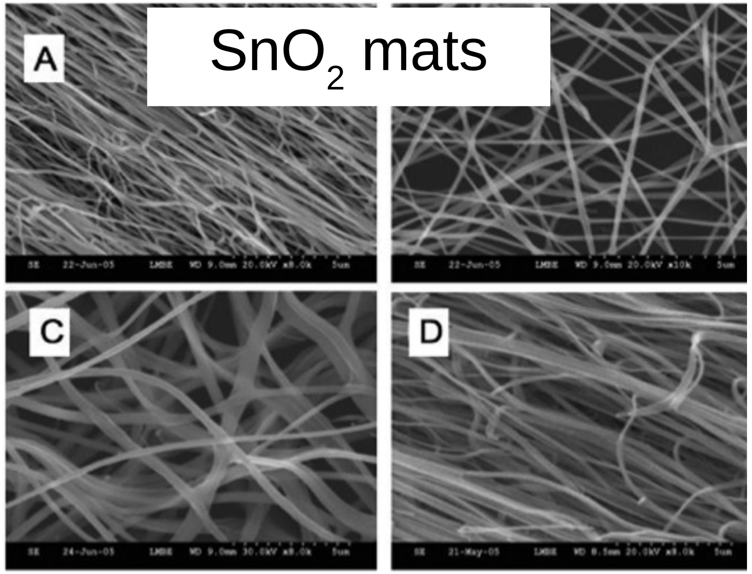
TABLE I. Foam types used in laser targets and their properties.

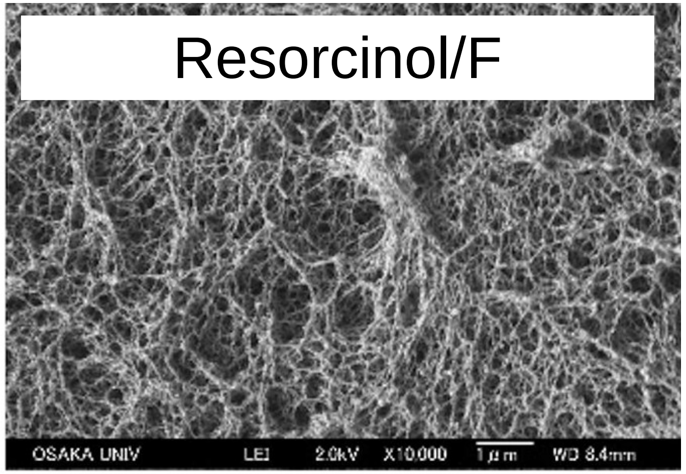
Foam class	Pore size range[a]	Density range (mg/cm^3)[b]	Element composition	High/low Z (e1)	Target dimensions (μm)
Aerogels					
Organic aerogels (RF)	nm	10–250	CHO	Low Z	200–600
Inorganic aerogels	nm	1–250	(Si, Ta, Ga, Al) O_2	Middle-High Z	200–600
Carbonized aerogels	nm	10–250	C	Low Z	200–600
PolyHIPE	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 laser-plasma experiments



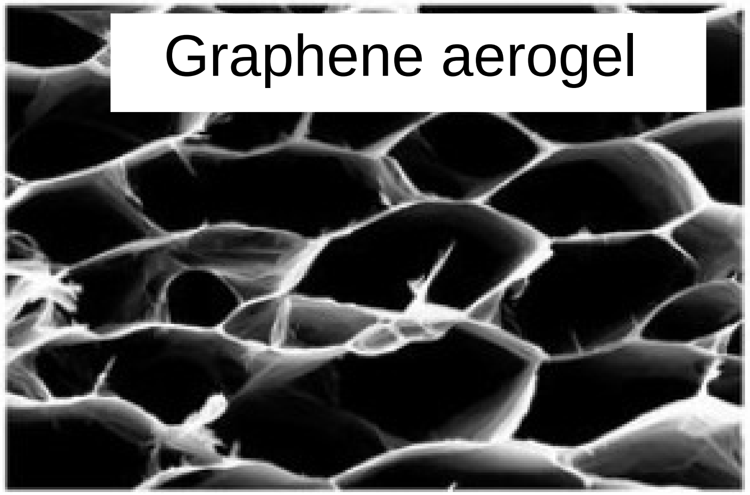






- Quasi-periodic networks
- Characterized by pore size

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



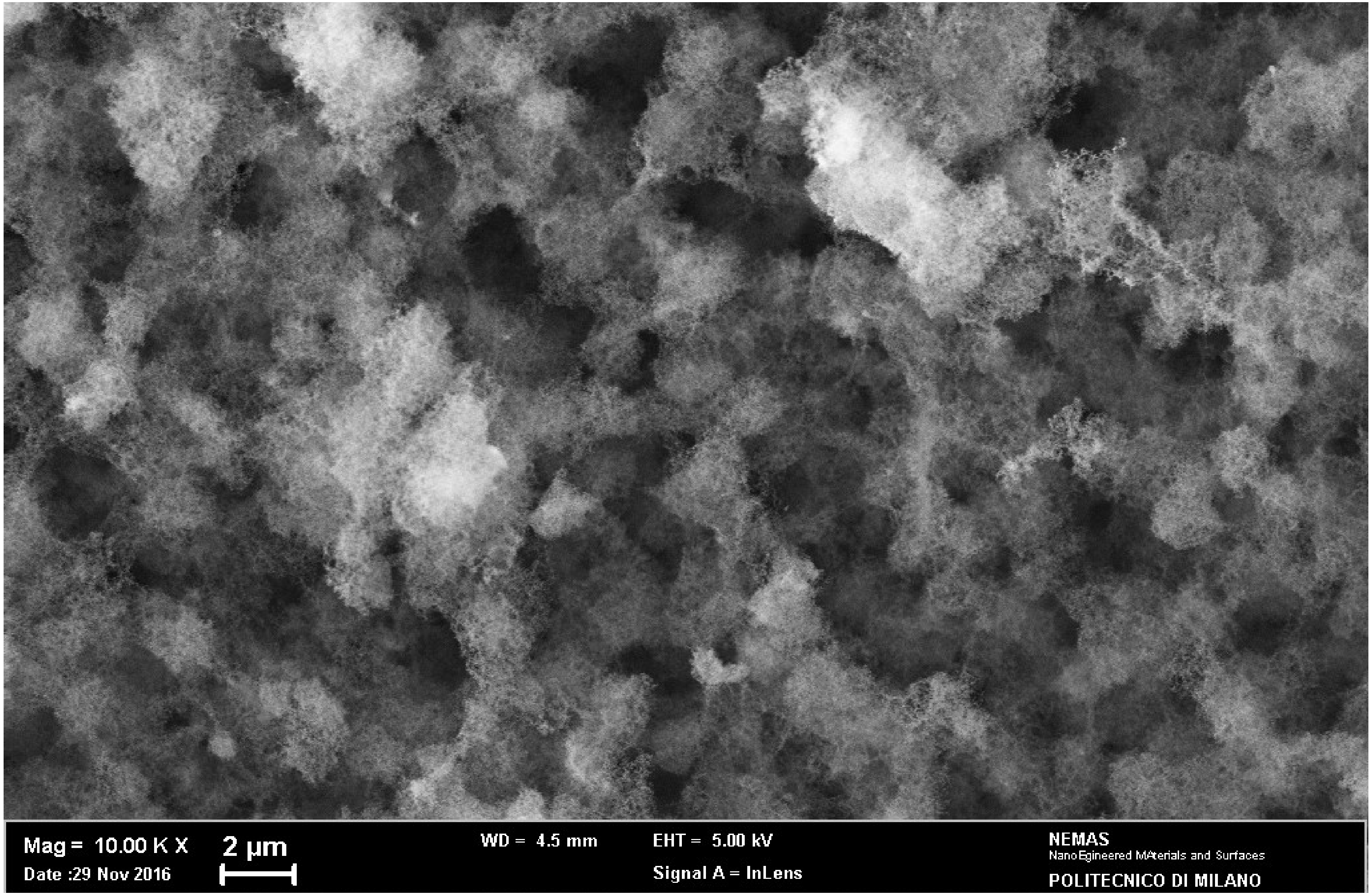
Why foam targets in laser-matter interaction?

Why Pulsed Laser Deposition of nanofoams?

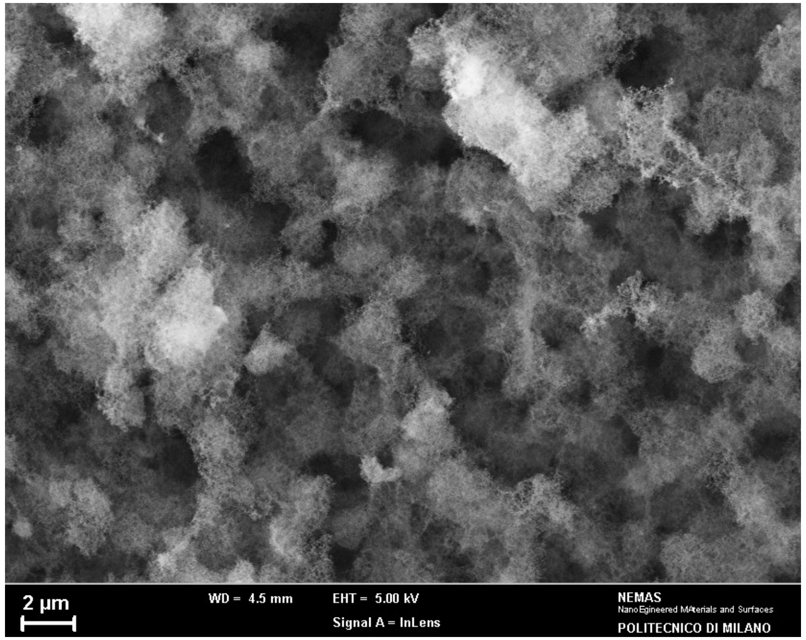
Features of PLD nanofoams

PLD nanofoam in laser-matter interaction & ICF

Pulsed Laser Deposited nanofoams look different



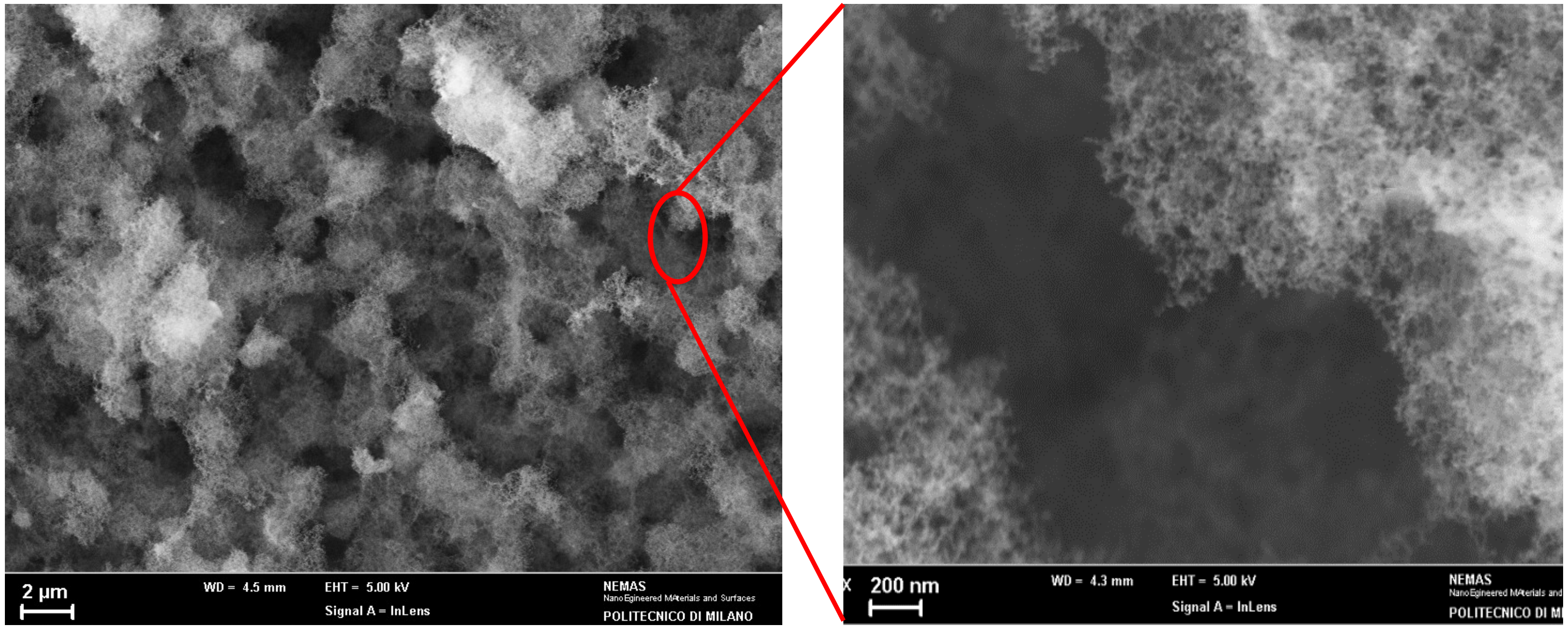
Pulsed Laser Deposited nanofoams



Arbitrary composition:
(pure C, metals, oxides,...)
Multi-scale structure

A. Zani et al., *Carbon*. **56**: (2013) 358–365
A. Maffini et al., *Physical Review Materials* **3** (2019) 083404
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

Pulsed Laser Deposited nanofoams



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Multi-scale structure

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

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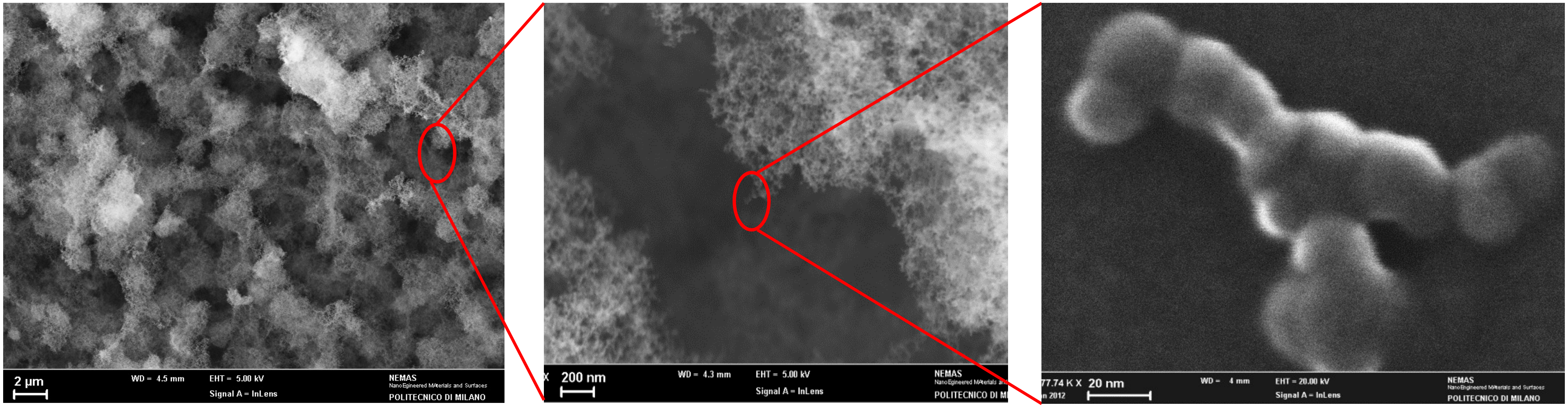

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Nanoparticle constituents:
NP radius (R_{np}) ~ 5 – 20 nm
NP density (ρ_{np}) ~ 50% – 100% of bulk

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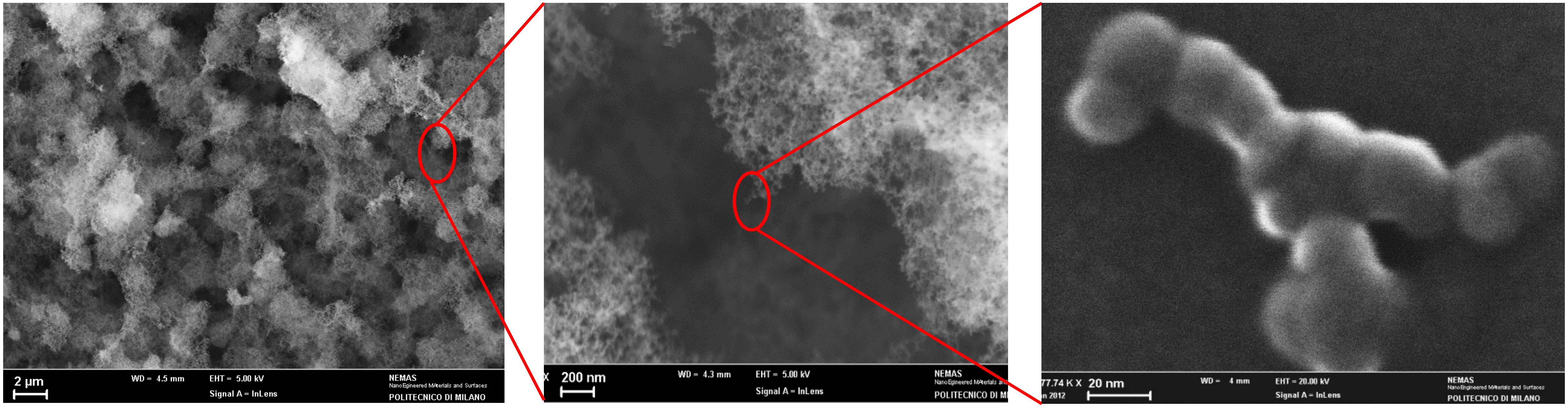
Pulsed Laser Deposited nanofoams



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Fractal density scaling

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

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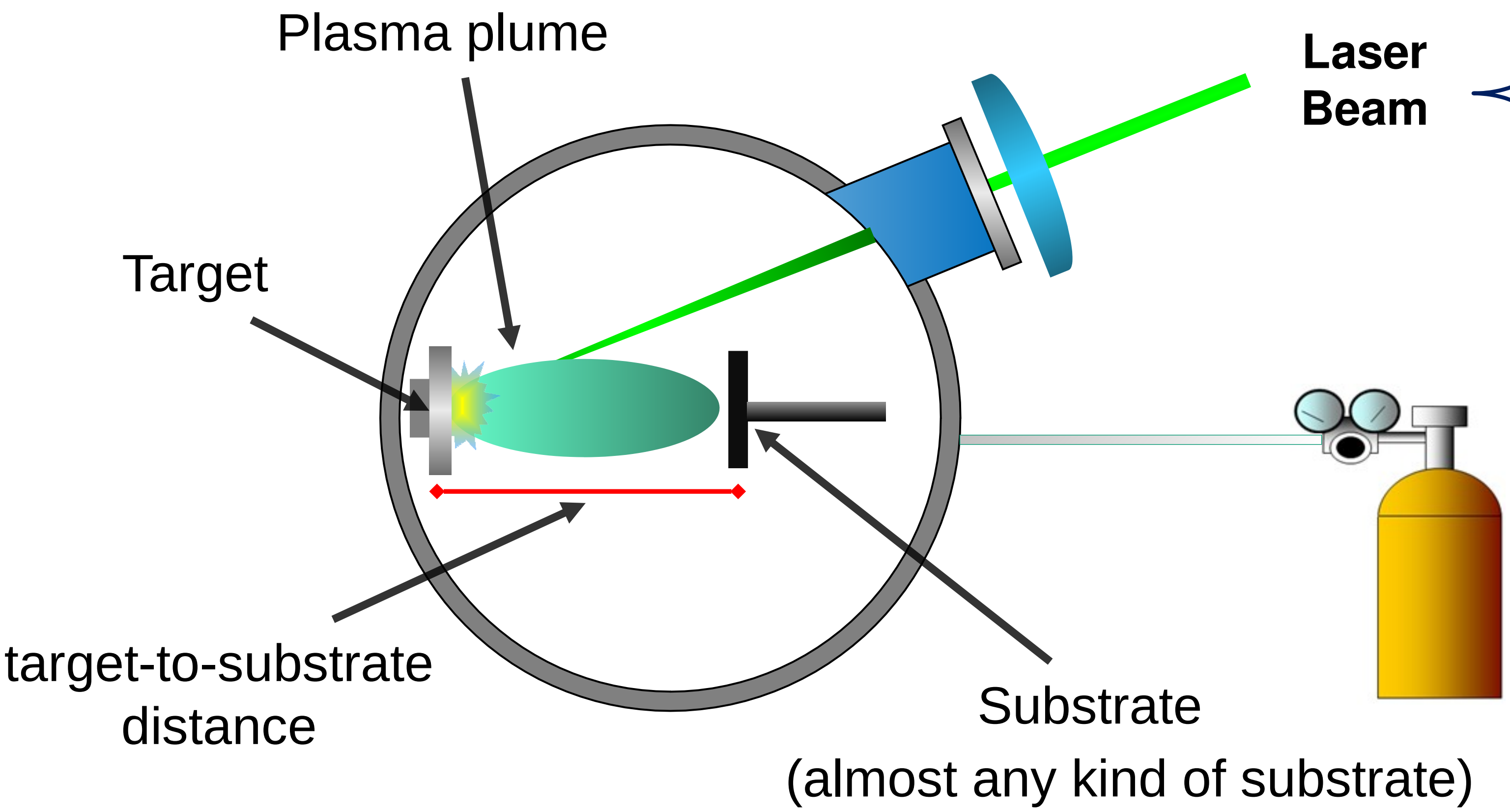


Conventional ns-PLD:
~ 5 ns pulse duration
~ 1 J pulse energy

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

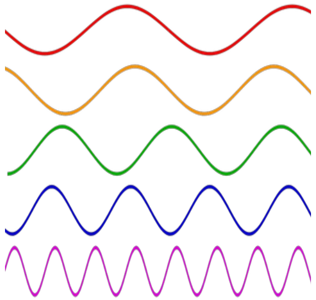
Foam properties control

Nano-scale
- Crystalline structure & composition
- Nanoparticle size

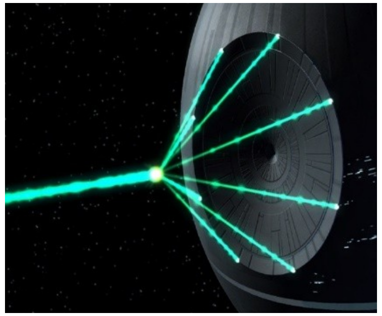
Micro-scale
- Aggregate size
- Morphology

Macro-scale
- Uniformity
- Thickness profile

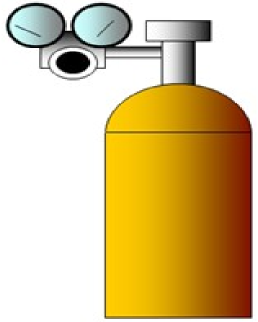
Pulse Duration



Laser Fluence



Gas pressure



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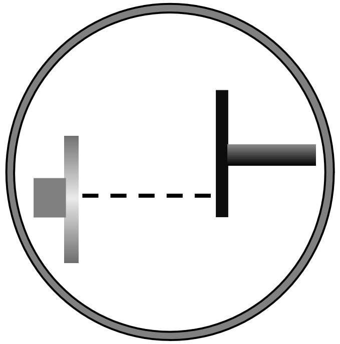
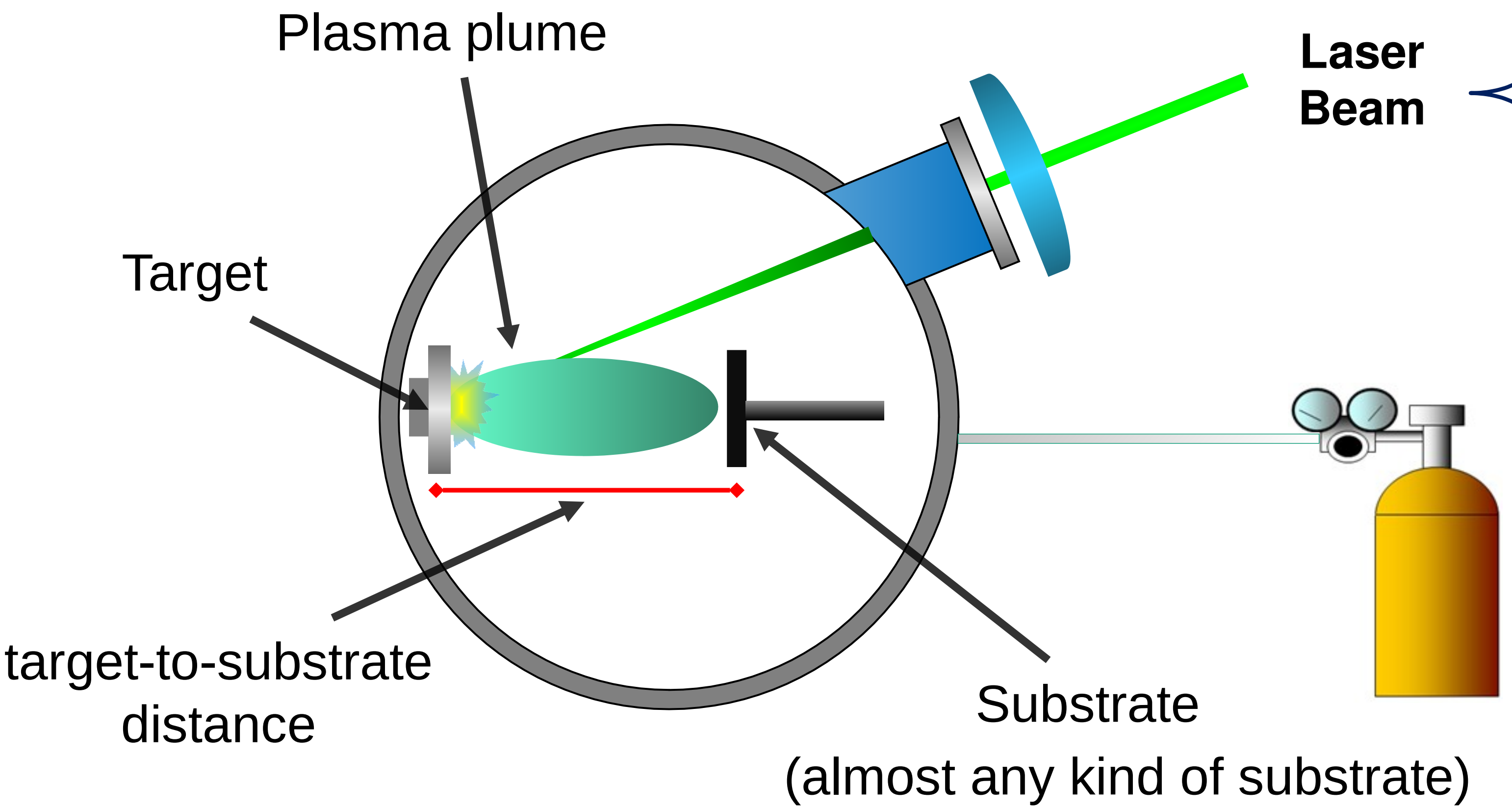


Deposition time

PLD process parameters

Pulsed Laser Deposition



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~ 1 J pulse energy

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

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

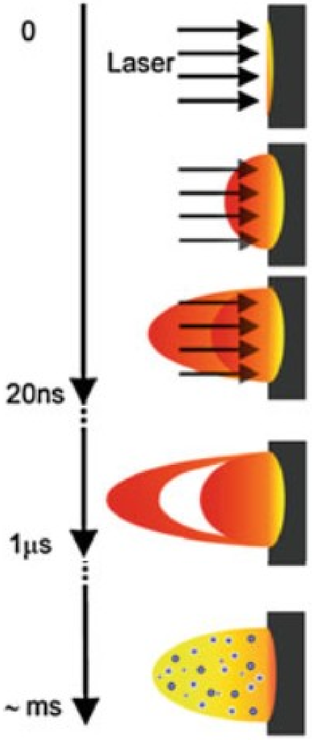
Unparalleled versatility

Complex, non-linear process

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

A “snowfall model” for nanofoam growth

Nanosecond PLD

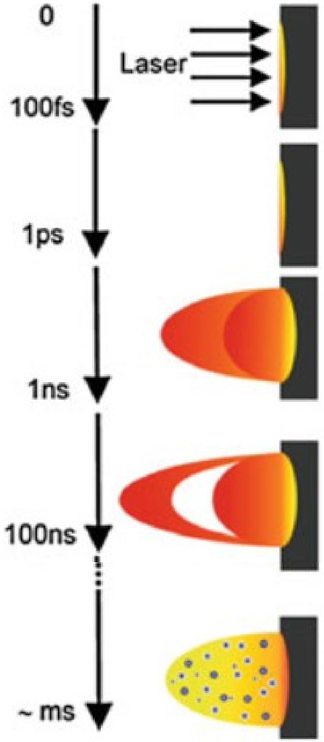


Thermal evaporation of atoms & ions

Laser-plasma plume interaction

Ablation 1

Femtosecond PLD



Laser-electron interaction

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404

A “snowfall model” for nanofoam growth

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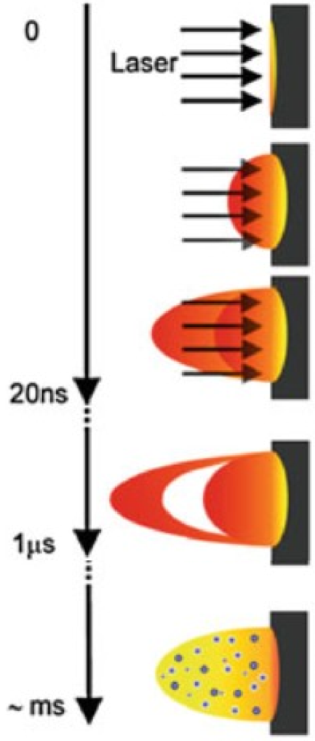

Thermal evaporation of atoms & ions

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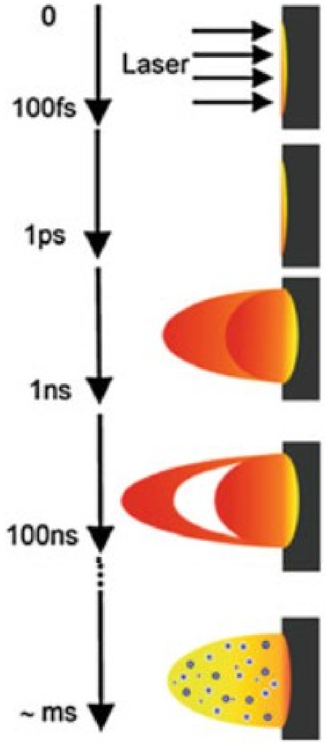
Nanoparticle nucleation

Ablation 1

2 **Nanoparticle Synthesis**

Femtosecond PLD



Laser-electron interaction

Direct ejection of nanoparticles

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404

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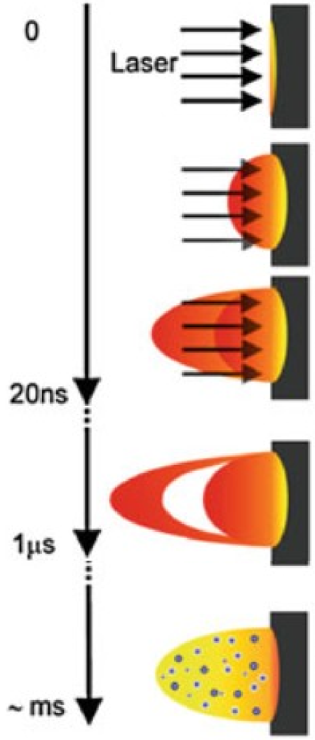

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Nanoparticle nucleation

Diffusion-limited Cluster-Cluster aggregation

Ablation 1

2 **Nanoparticle Synthesis**

Aggregate formation 3

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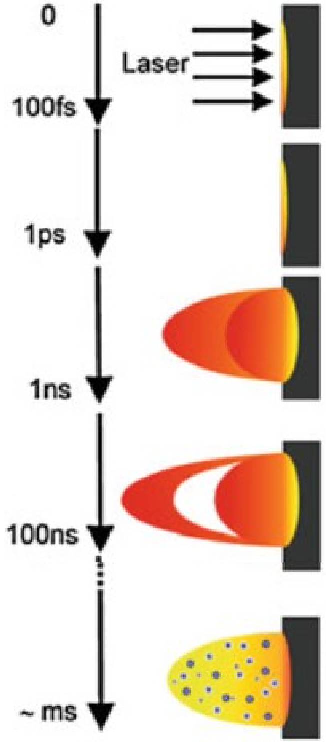

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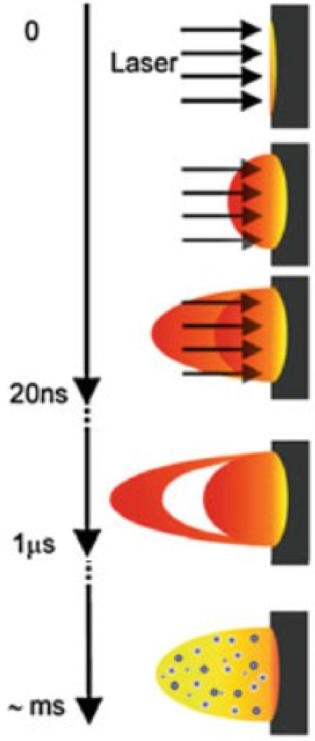

Thermal evaporation of atoms & ions

Laser-plasma plume interaction

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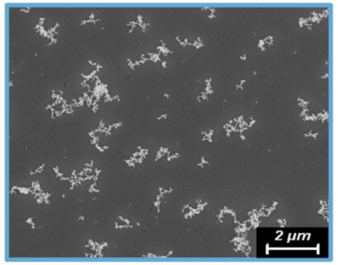


Aggregate landing

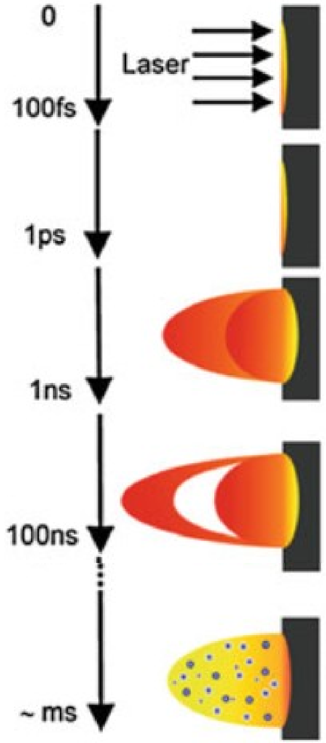
Ablation 1

2 **Nanoparticle Synthesis**

Aggregate formation 3

4 **Foam growth by aggregate layering**

Femtosecond PLD



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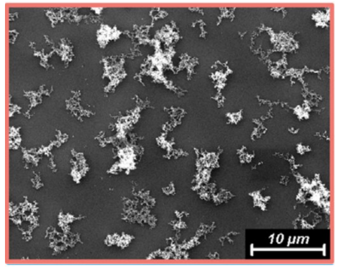


Aggregate landing

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404

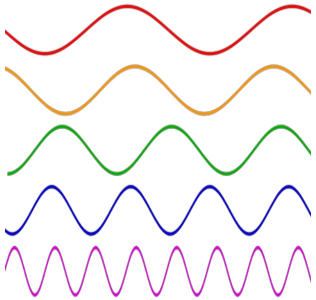
Foam properties control

Nano-scale
- Crystalline structure & composition
- Nanoparticle size

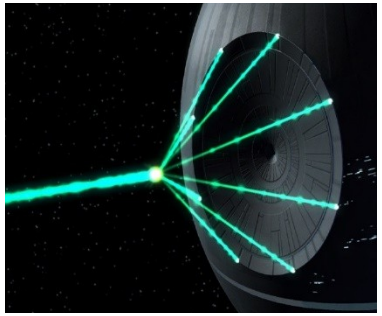
Micro-scale
- Aggregate size
- Morphology

Macro-scale
- Uniformity
- Thickness profile

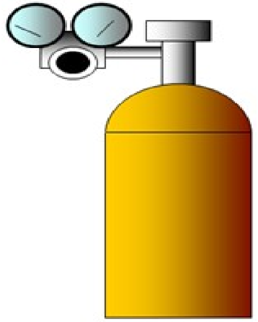
Pulse Duration



Laser Fluence



Gas pressure



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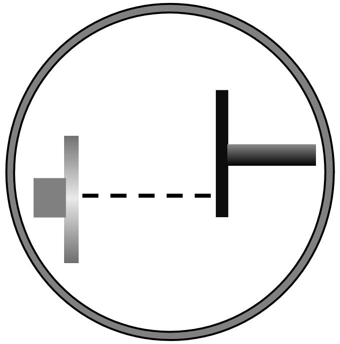
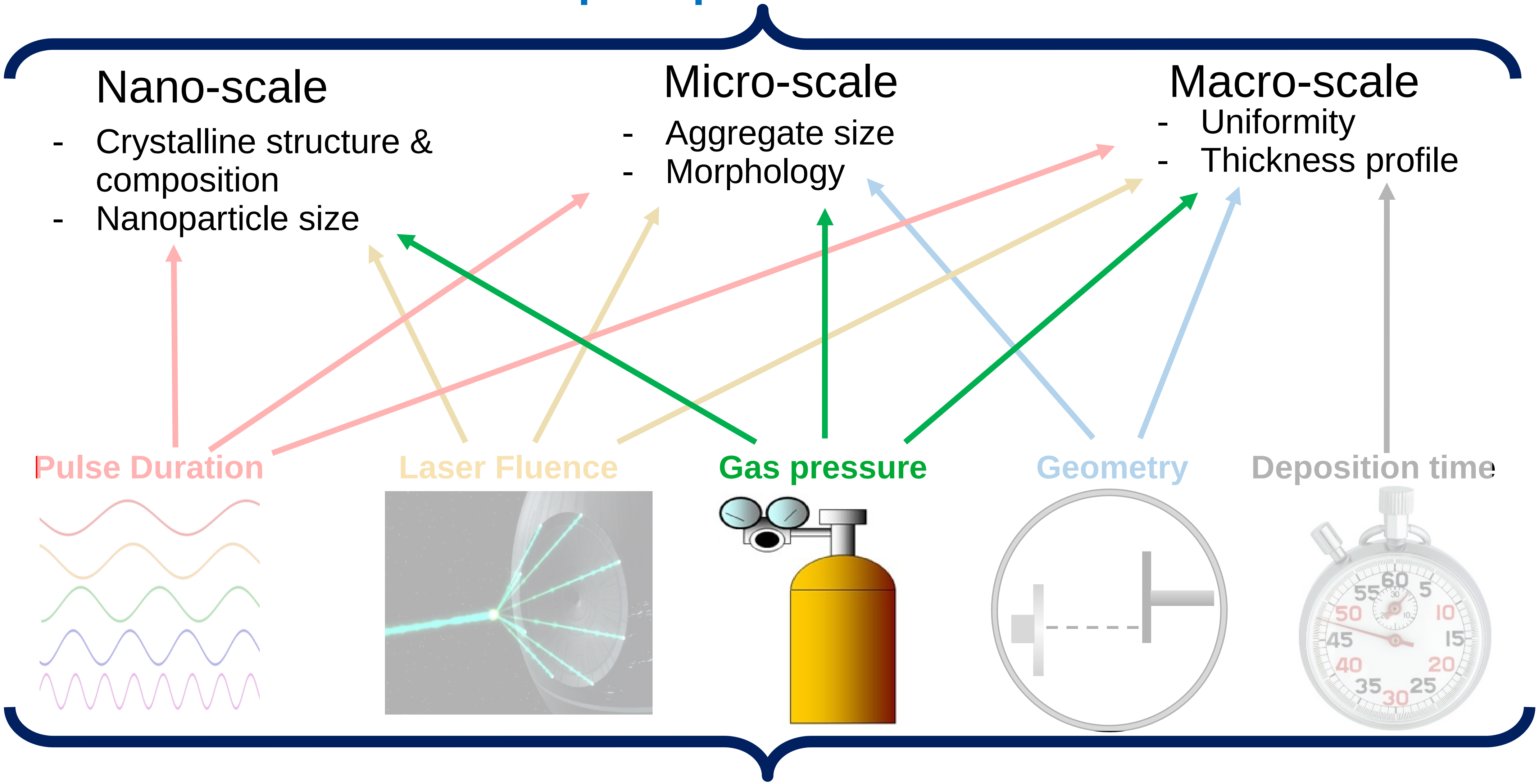


Deposition time

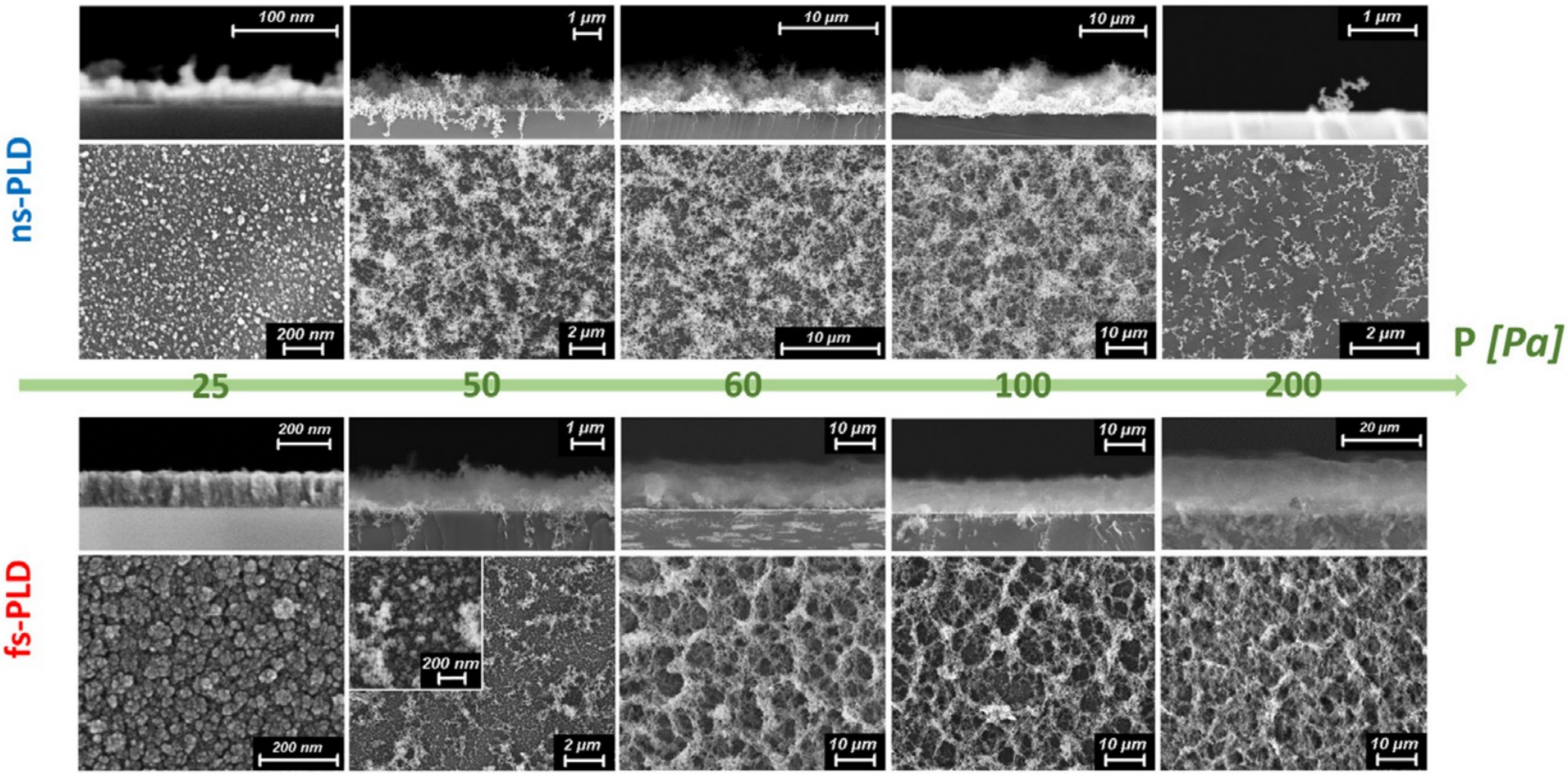
PLD process parameters

Foam properties control



PLD process parameters

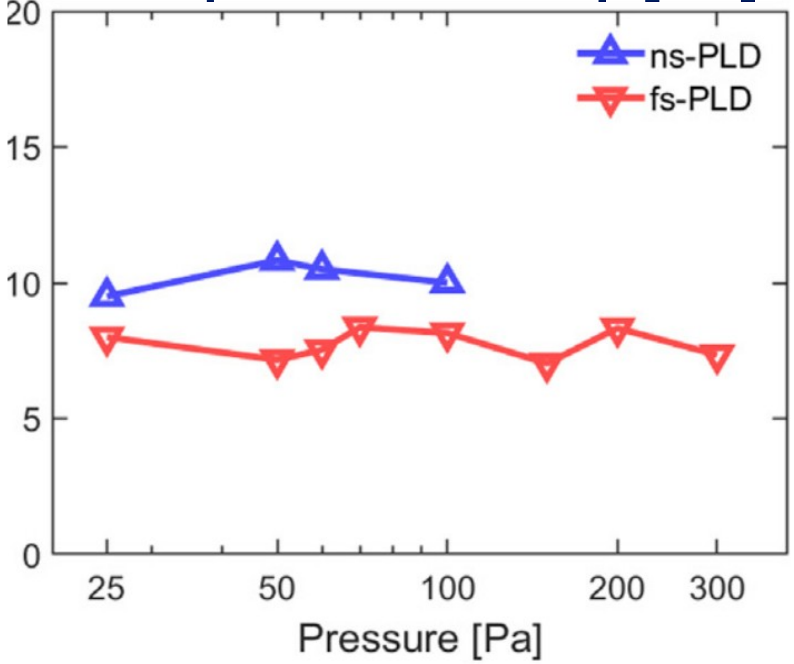
Example: the role of deposition pressure



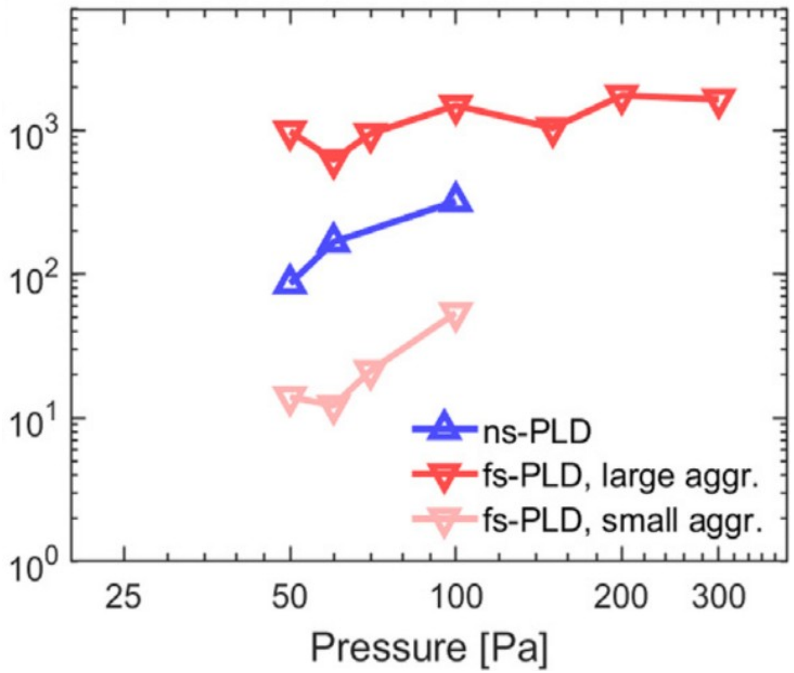
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

Nanofoam analysis at nano- and micro-scale

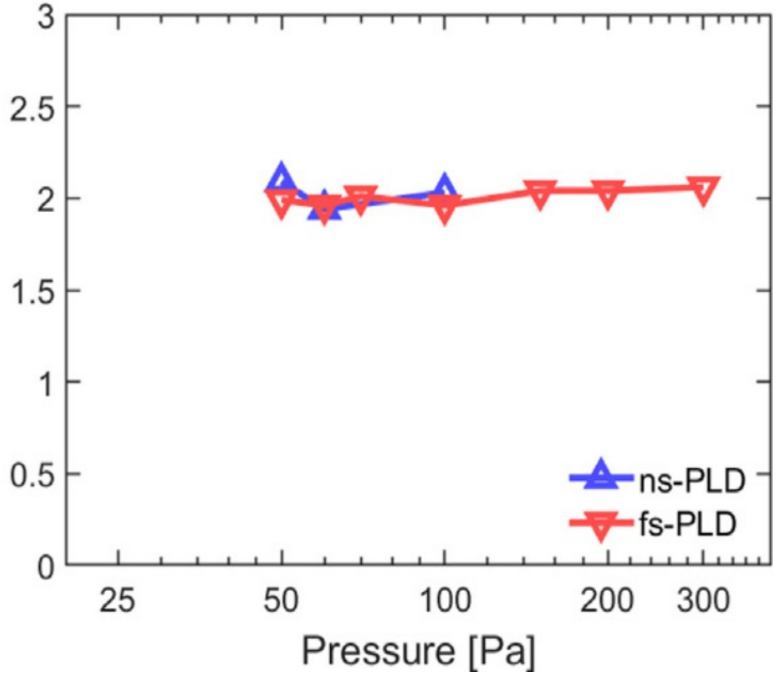
Nanoparticle size Rnp [nm]



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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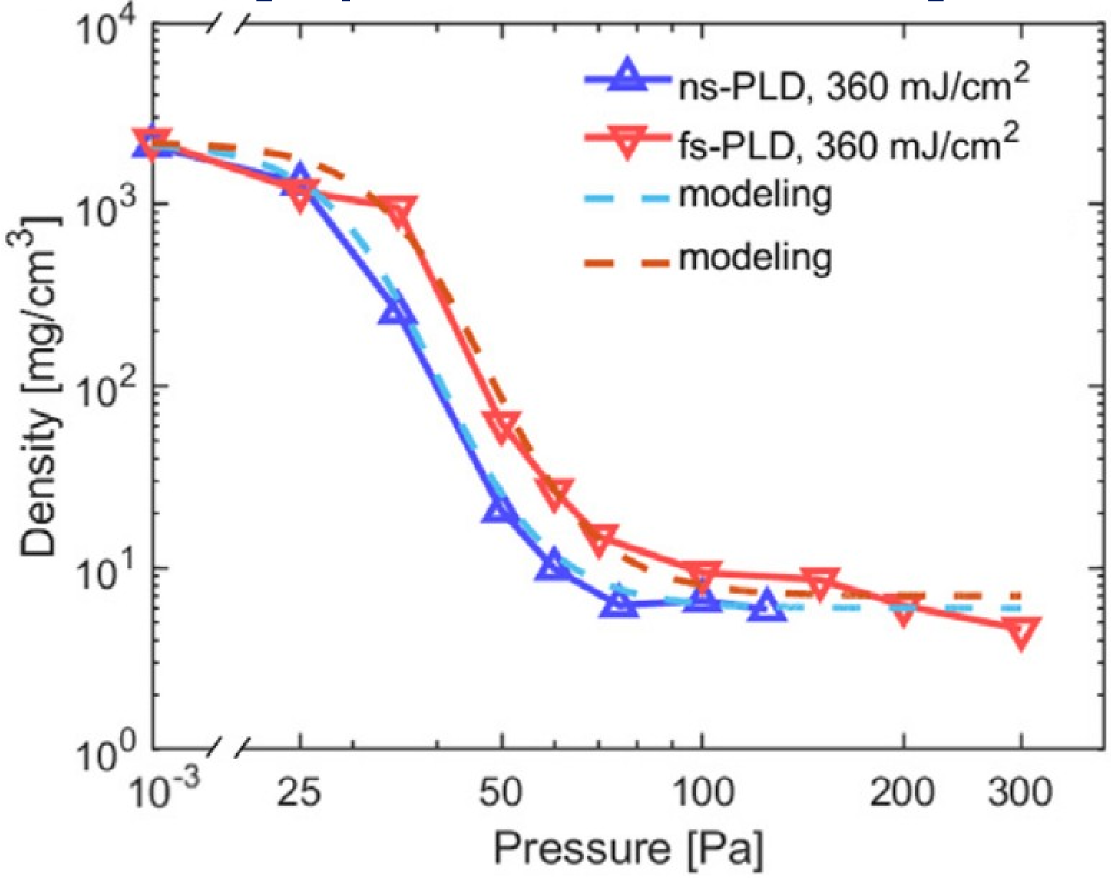
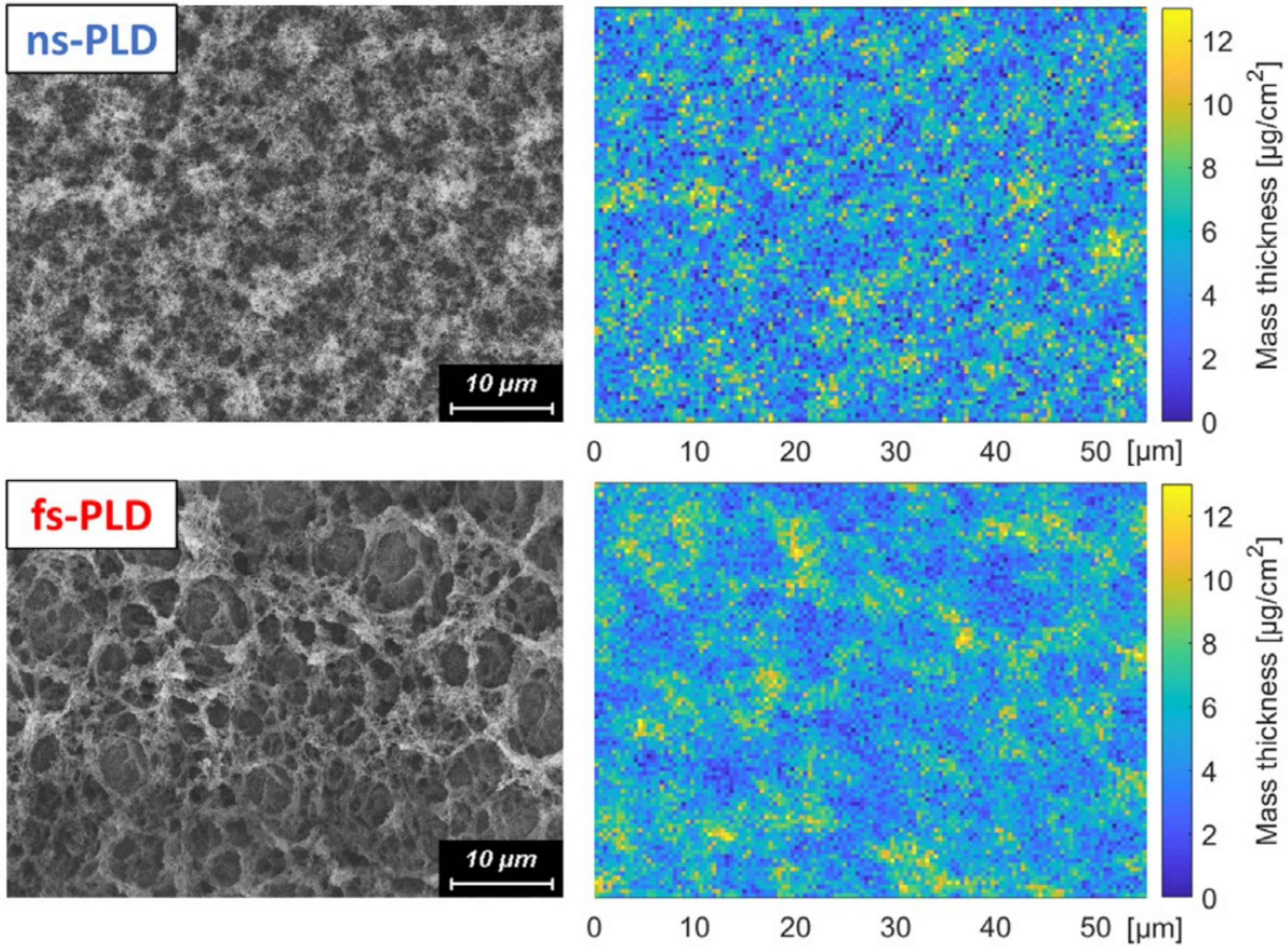
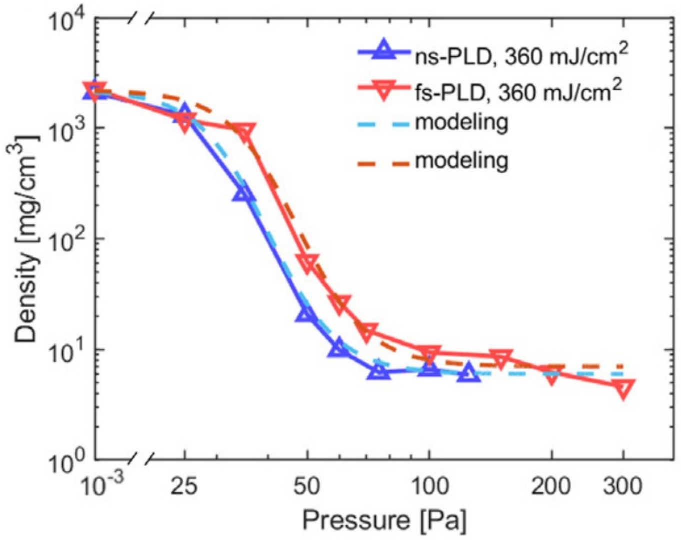
Fine tuning of nanofoam density

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)

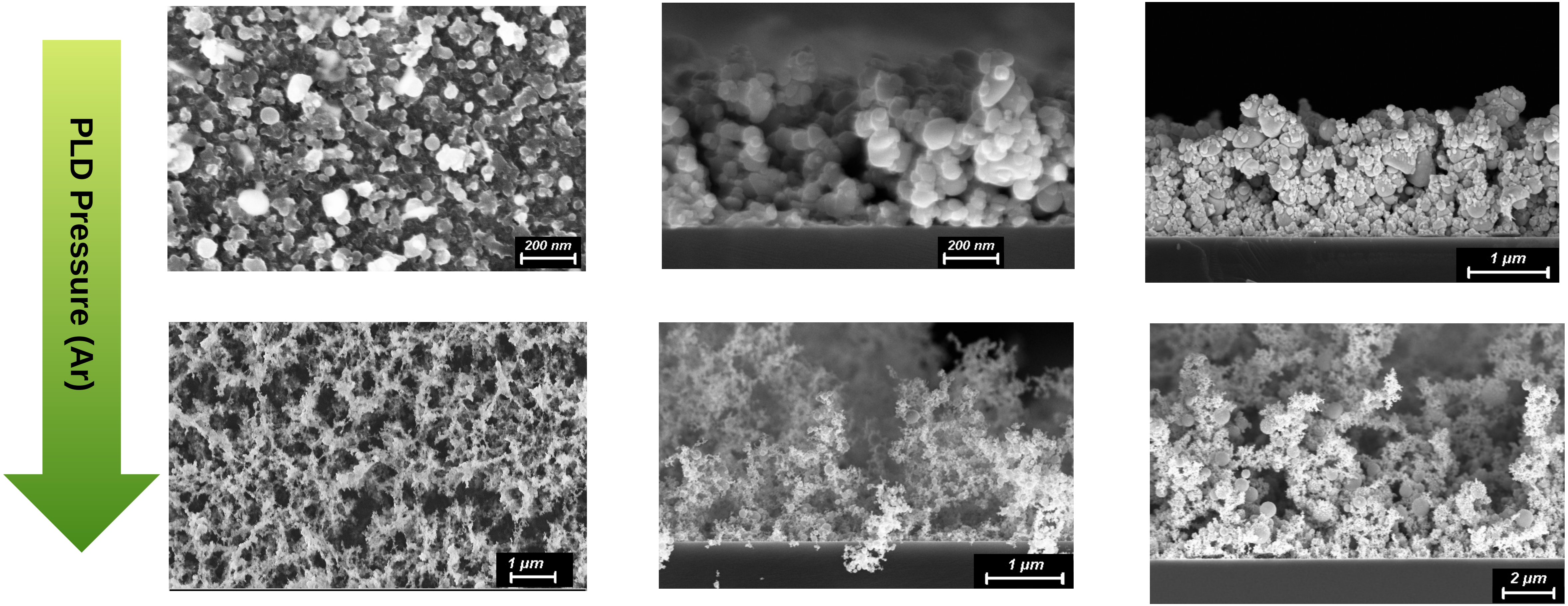
Density [mg/cm^3]

~10 mg/cm^3

~150 mg/cm^3

PLD works fine for most of elements

Boron | Titanium | Gold



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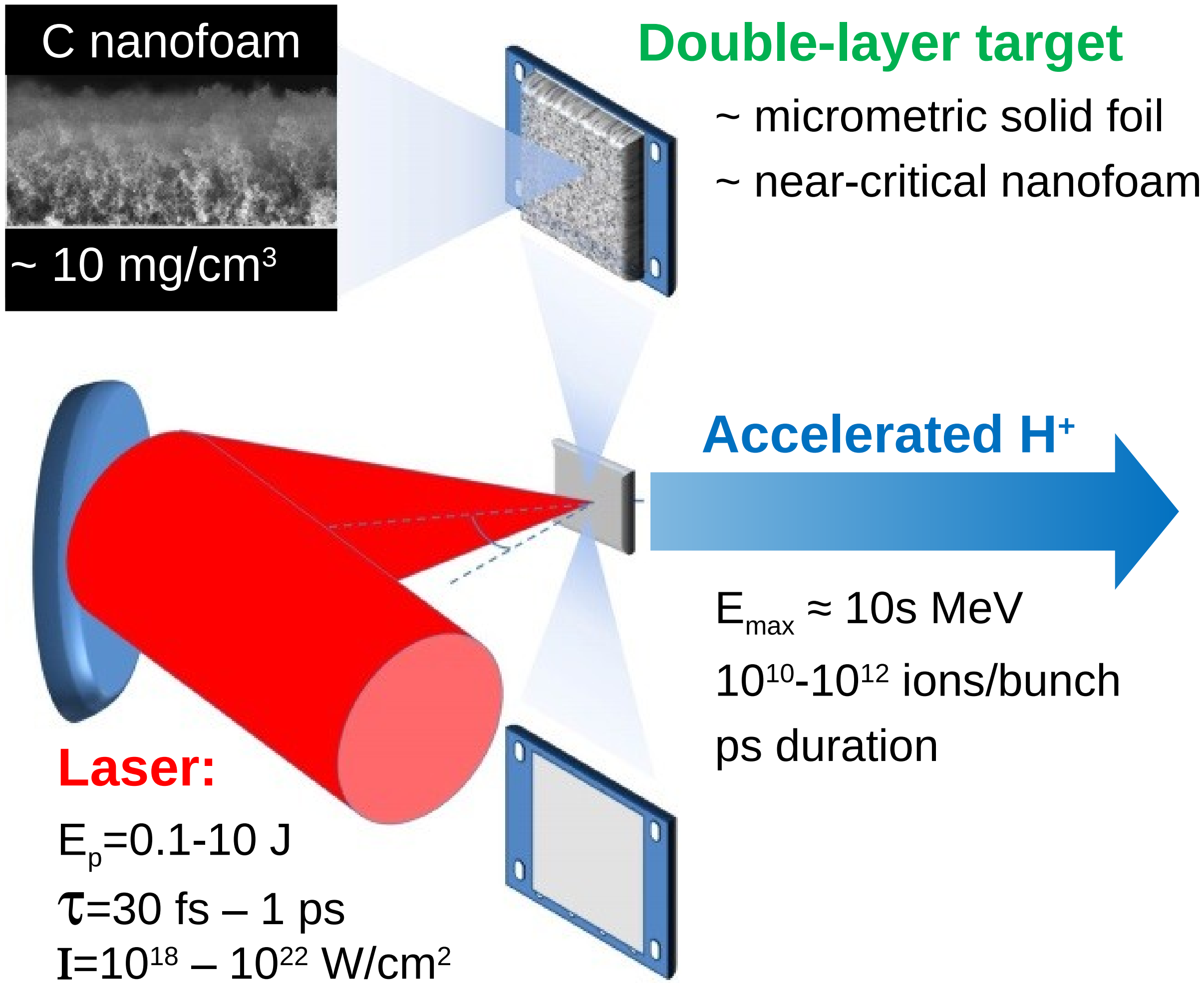
Nanofoams for advanced TNSA



M. Passoni et al., *Plasma Phys. Control. Fus.* **56** (2014)
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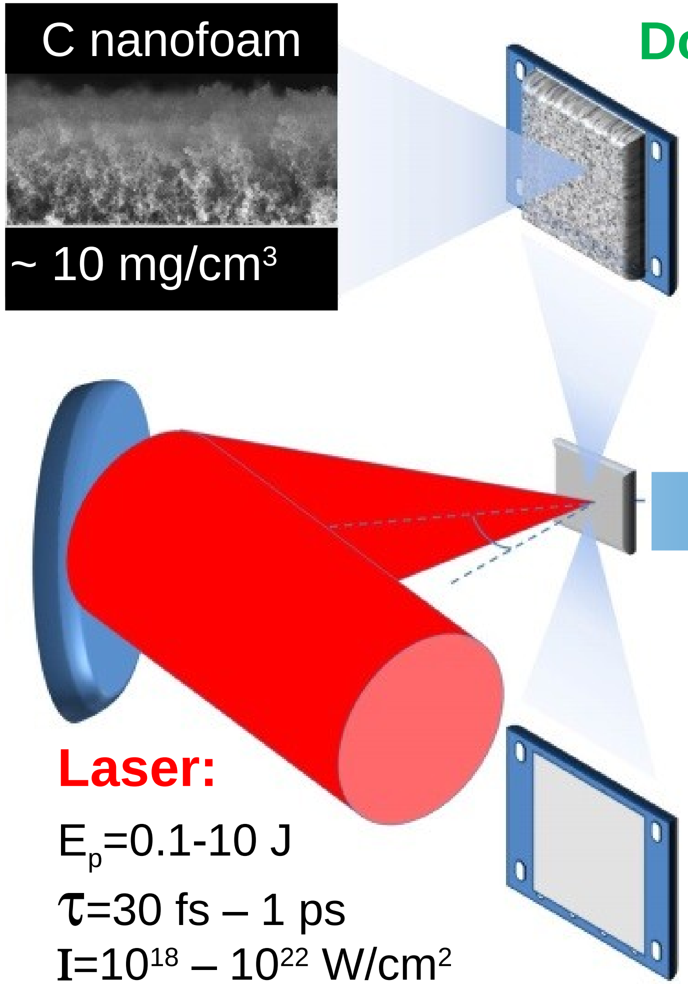
A. Pazzaglia et al., *Communications Physics* **3** (2020)

Nanofoams for advanced TNSA



Double-layer target

~ micrometric solid foil

~ near-critical nanofoam

Accelerated H^+

$E_{max} \approx$ 10s MeV

10^{10}-10^{12} ions/bunch

ps duration

Laser:

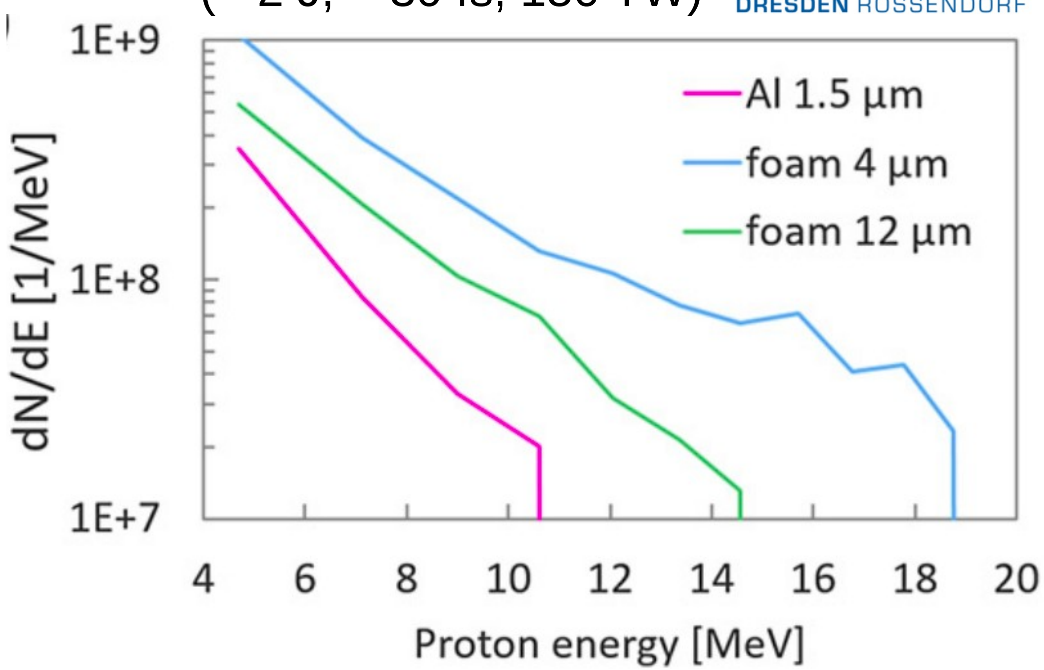
E_p=0.1-10 J

τ=30 fs – 1 ps

$I=10^{18} - 10^{22}$ W/cm^2

Experiments @ Draco
(~ 2 J, ~ 30 fs, 150 TW)

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



~ x 2 in maximum energy!
~ x 4 in number of protons!

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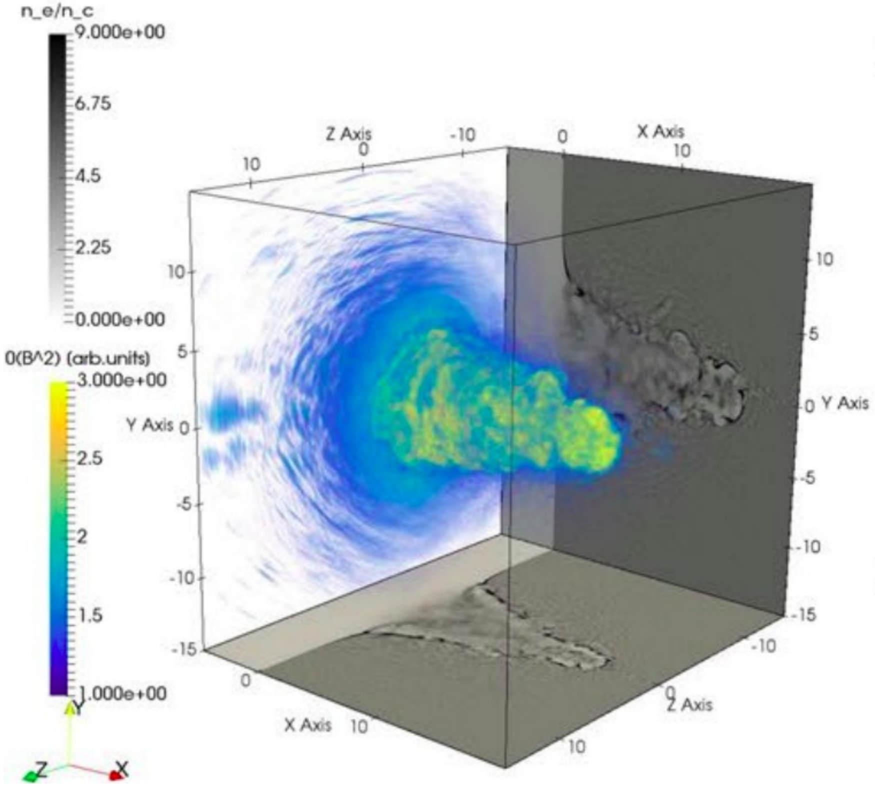
M. Passoni et al., *Phys. Rev. Accel. Beams* **19**, (2016)
A. Pazzaglia et al., *Communications Physics* **3** (2020)

I. Prencipe et al., *New Jour. Physics* **23.9** (2021)

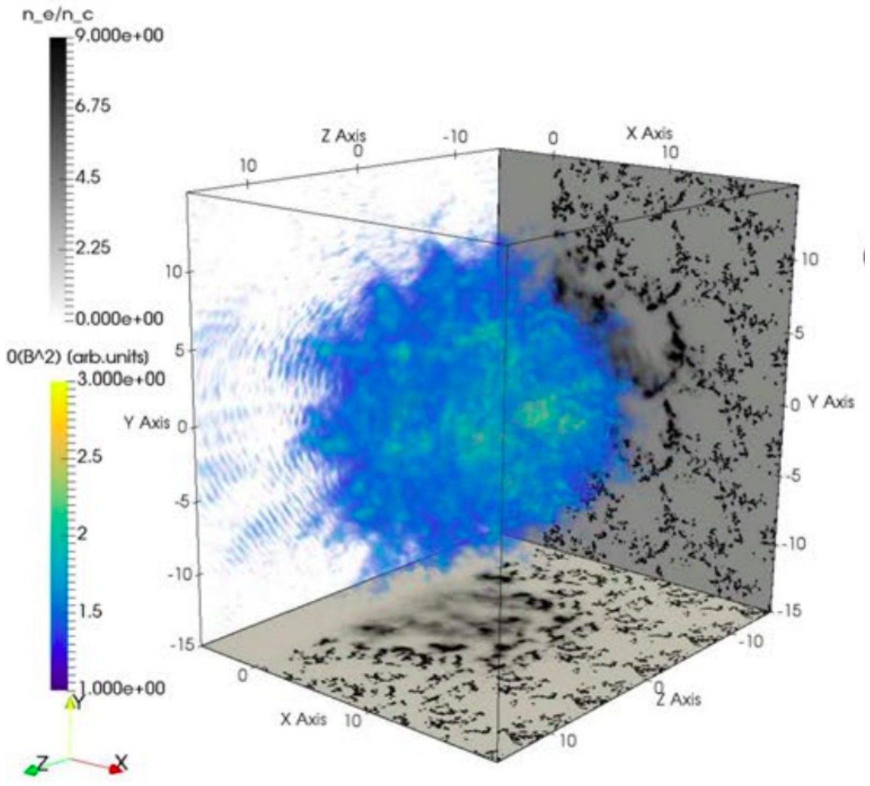
Modeling nanofoam interaction with fs lasers

3D **PIC simulations**: same average density, homogeneous vs nanofoam plasma, a0~ 5 – 45, pulse duration 30 fs

Near-critical, homogeneous



Near-critical, nanofoam

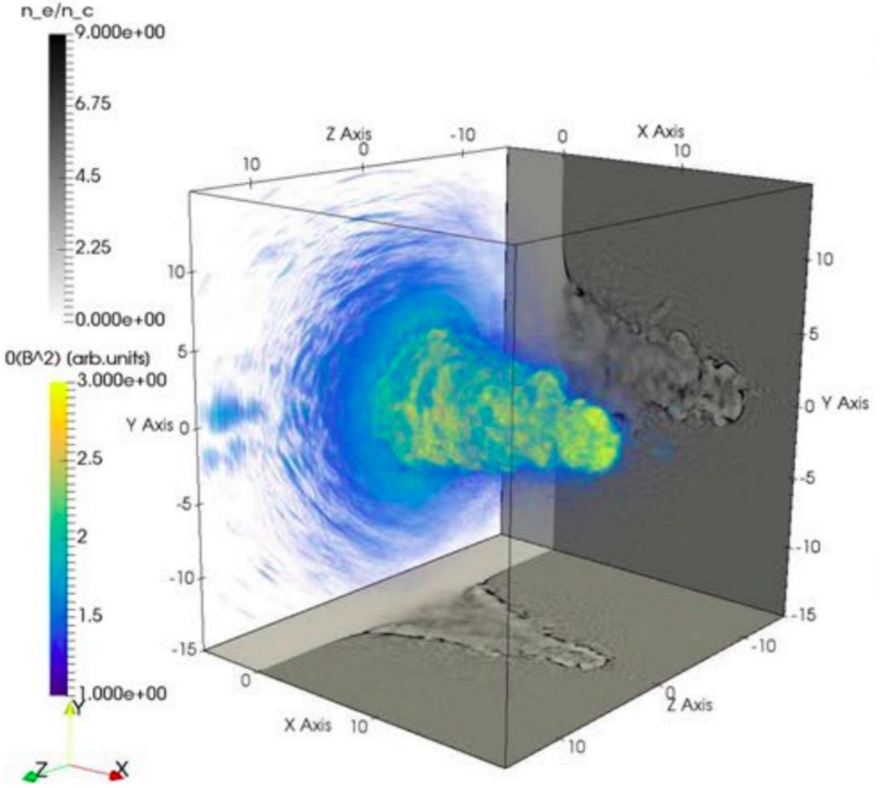


L. Fedeli et al., *Scientific reports.* **8**:3834 (2018)

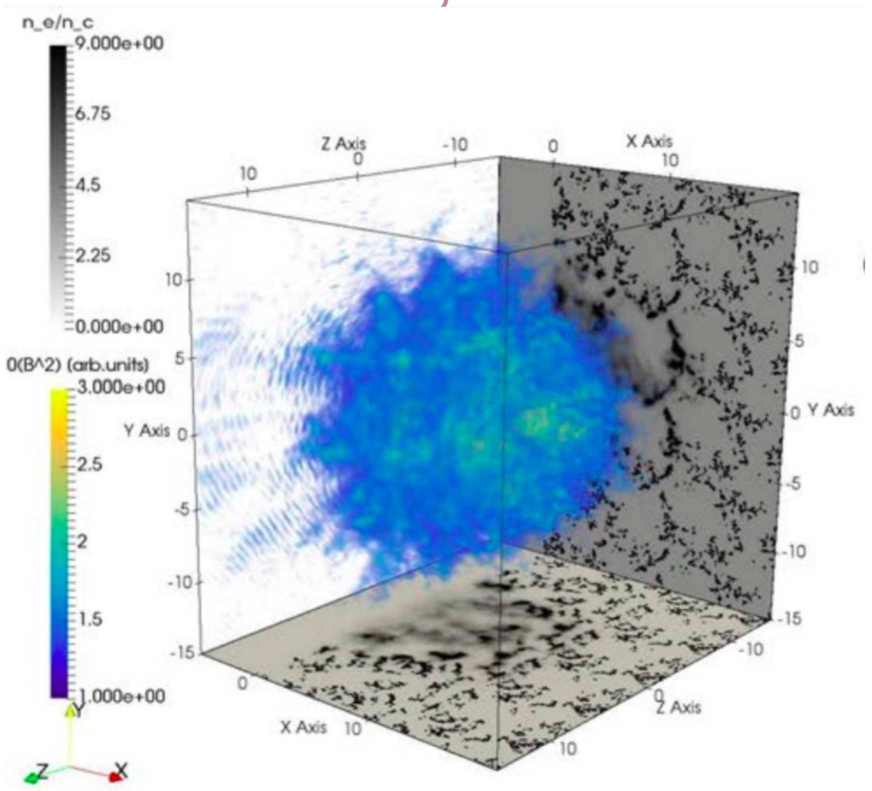
Modeling nanofoam interaction with fs lasers

3D **PIC simulations**: same average density, homogeneous vs nanofoam plasma, a0~ 5 – 45, pulse duration 30 fs

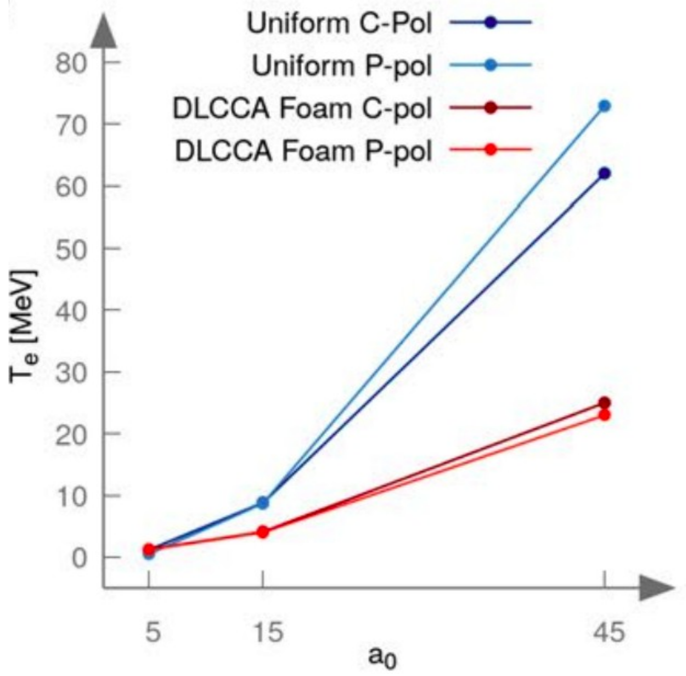
Near-critical, homogeneous



Near-critical, nanofoam



Nanostructure matters!

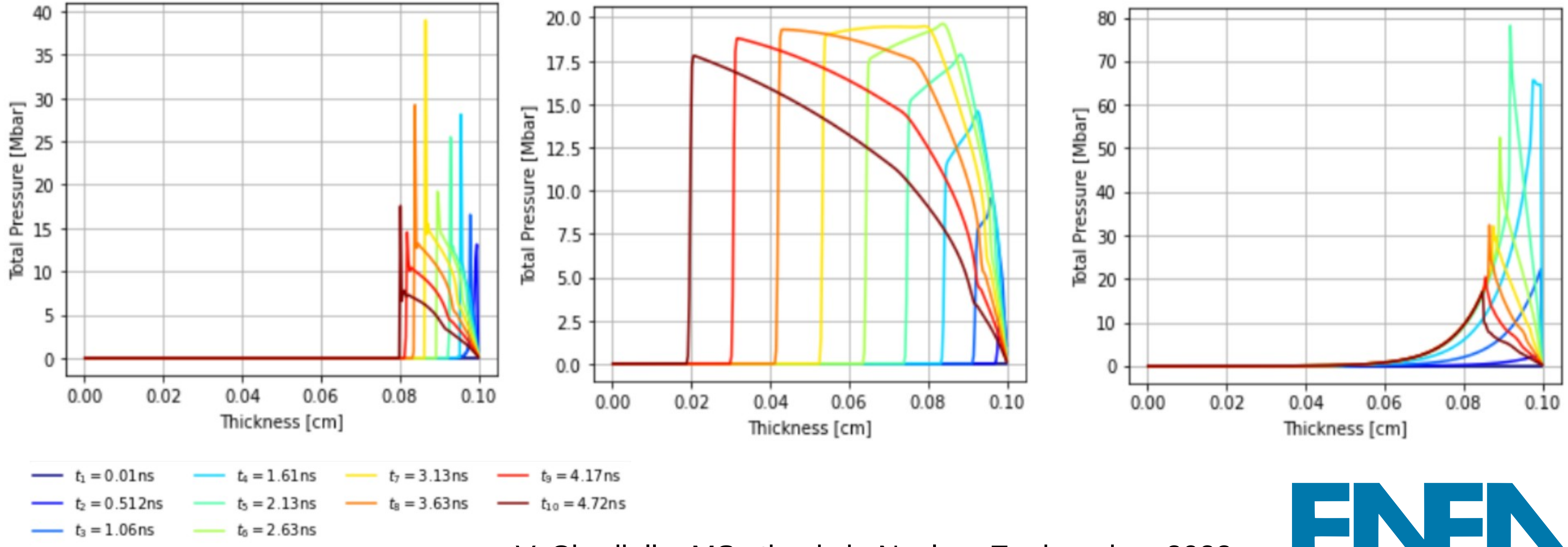


L. Fedeli et al., *Scientific reports.* **8**:3834 (2018)

Modeling nanofoam interaction with ns lasers

1D **hydro simulations** with MULTI-FM. 100% **Carbon**. Same areal density. Pulse duration ~2.5 ns. I=10 ^{14} W/cm^2

High Density Carbon | **Near-critical, homo C** | **Near-critical, C nanofoam**

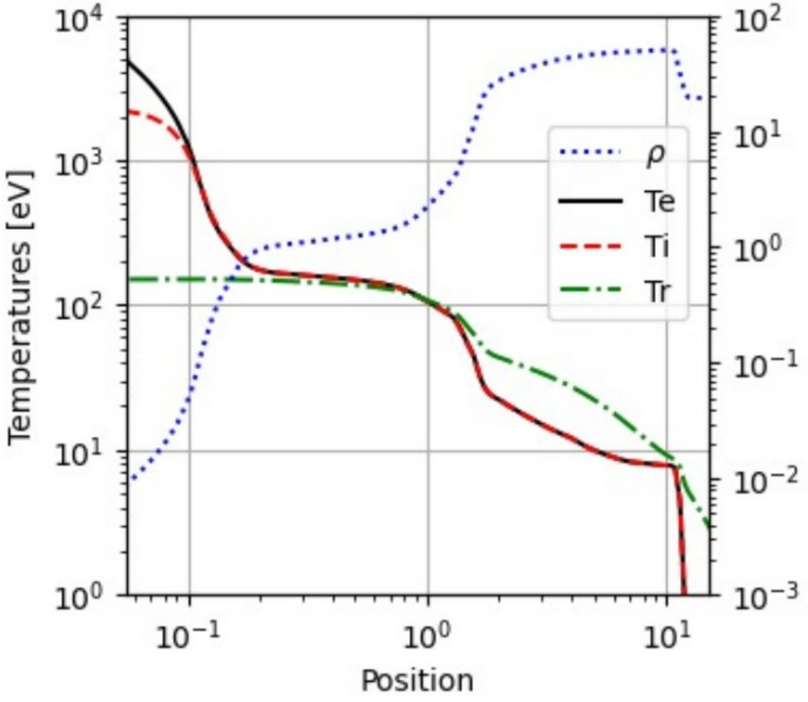


V. Ciardiello, MSc thesis in Nuclear Engineering, 2022

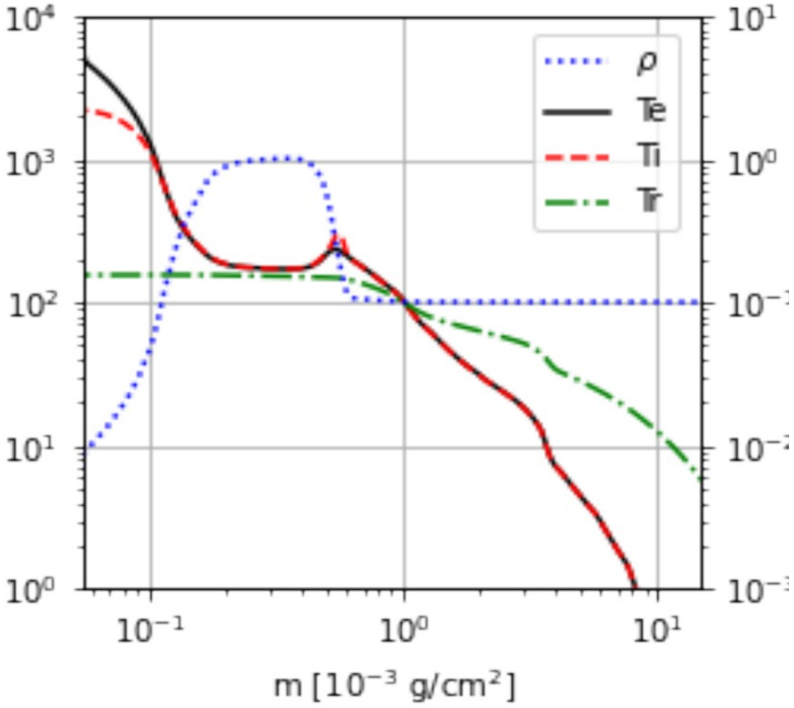
Modeling nanofoam interaction with ns lasers

1D **hydro simulations** with MULTI-FM. 100% **Gold**. Same mass density. Pulse duration ~2.5 ns. I=10^{14} W/cm^2

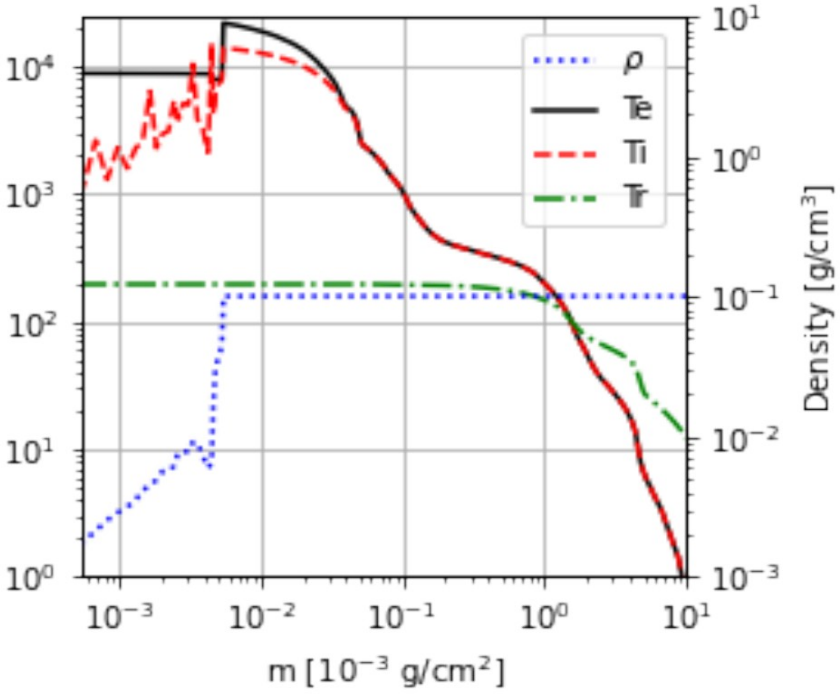
Bulk Au



Low density homo Au



Low density Au nanofoam



V. Ciardiello, MSc thesis in Nuclear Engineering, 2022

Conclusions and perspectives

- PLD as a **versatile alternative** to conventional techniques
    - PLD nanofoams have **potential** application also **in ICF**

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Conclusions and perspectives

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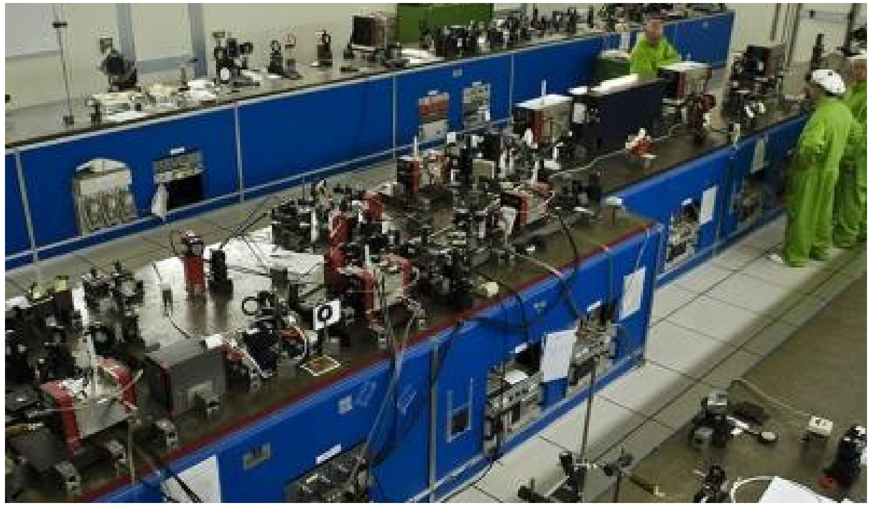
  - PLD nanofoams have **potential** application also **in ICF**
    - Can we trust 1D hydro simulation? Will the nanostructure survive long enough in ns regime? (and so on…)
      - **Experiments @ ABC are planned!**



ABC @ ENEA Frascati

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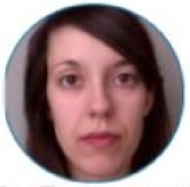
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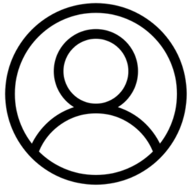
F. Gatti


F. Mirani


M. Galbiati


D. Orecchia

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Thank you for your attention!