Femtosecond pulsed laser deposition as a universal tool for nanofoam synthesis

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NanoLab

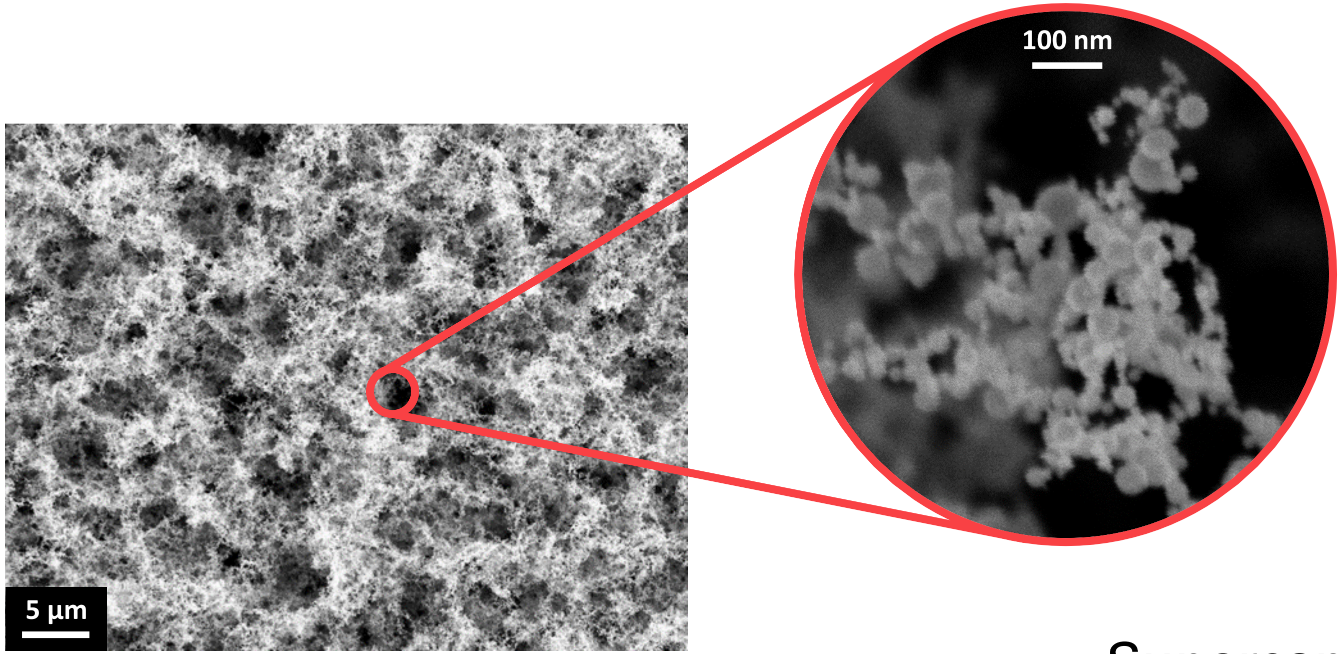
EUROfusion

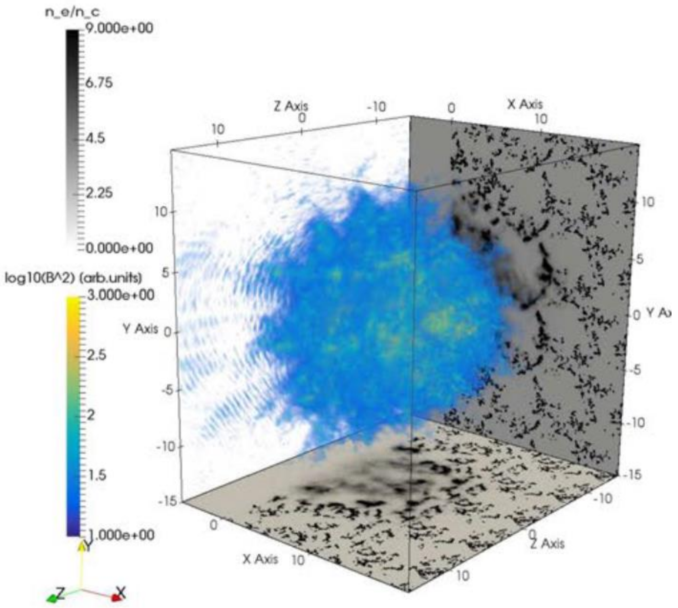
COLA 2024
17 th International Conference on Laser Ablation

COLA 2024

Hersonissos – **4** oct **2024**

Nanostructured materials and nanofoams





Fedeli L. et al., *Scientific reports* 8.1, 2018

Disordered **web-like** structures

Substantial **surface area**

Density as low as a **few mg/cm³**

- Supercapacitors
- Catalysis
- Gas sensing
- High intensity **laser-matter interaction**

Efficient laser energy absorption

Nanostructure **effect**

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Nanostructured materials synthesis

- Nanostructure properties **control**
- **Flexibility**

Chemical techniques

Top-down

Bottom-up

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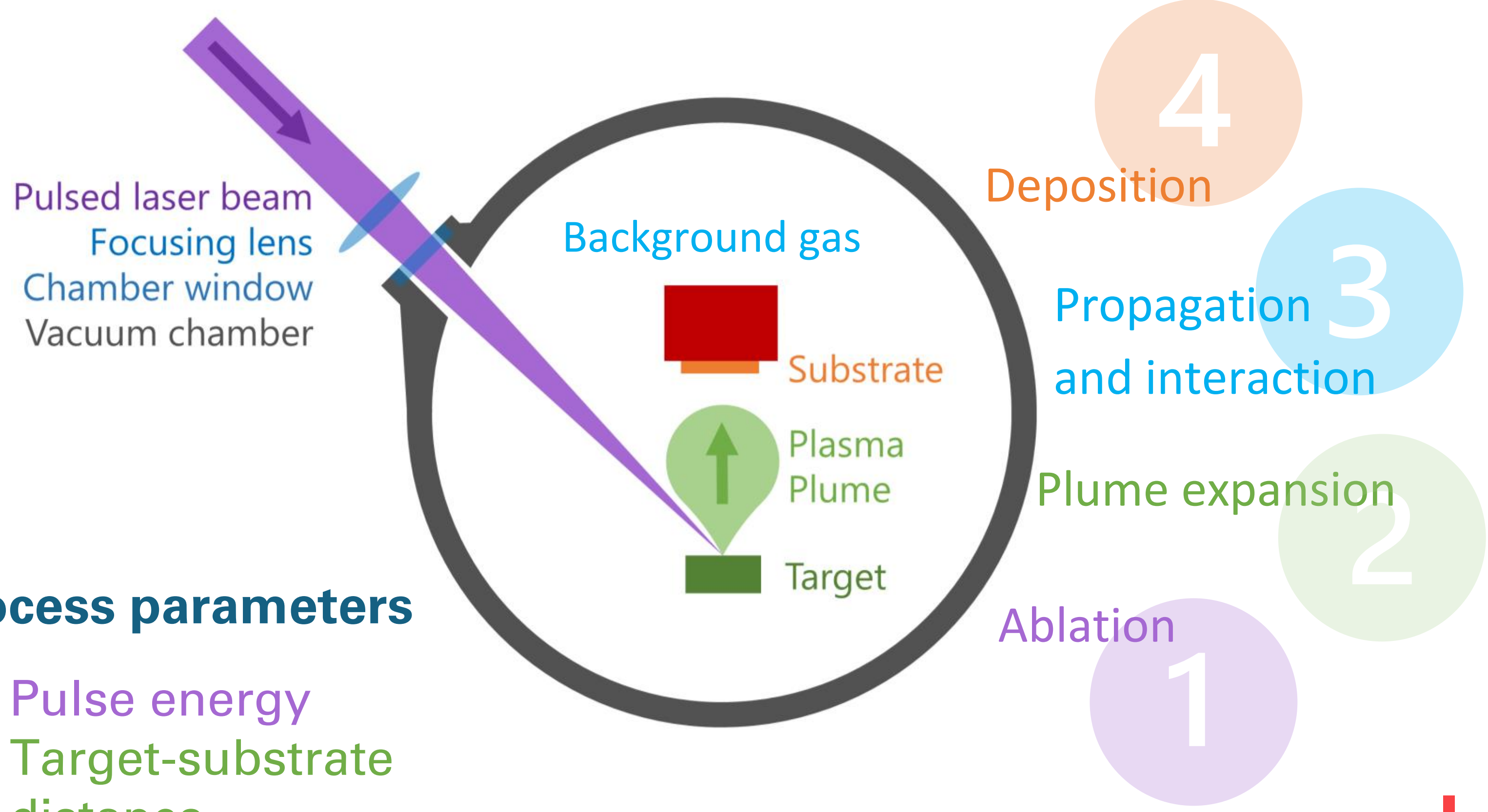
Pulsed Laser Deposition (PLD)



Process parameters

- Pulse energy
- Target-substrate distance
- Background gas pressure
- Substrate

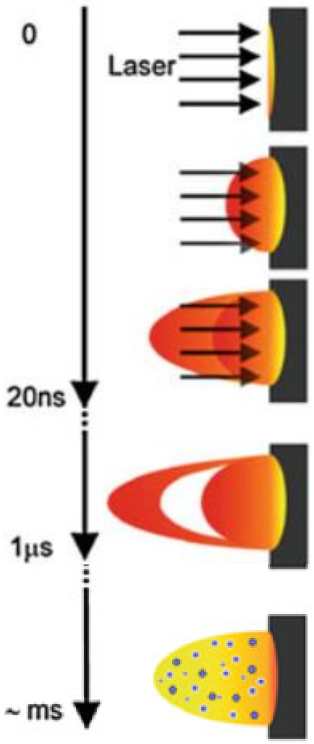
Laser **pulse duration**
- ns-PLD
- fs-PLD

Introduction

ns-PLD and fs-PLD techniques

Different **ablation regimes**

ns-PLD

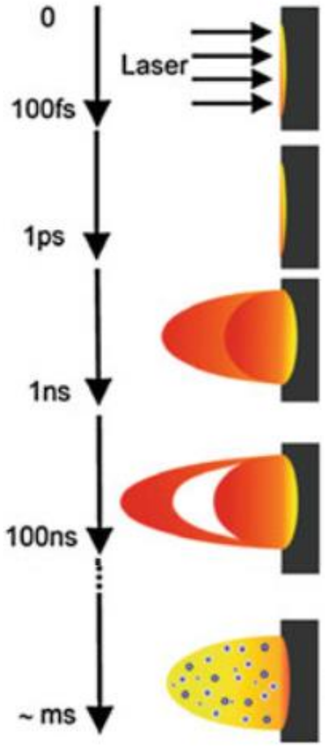


Thermal vaporization of **atoms** and **ions**

Plasma expansion

Plume condensation

fs-PLD



Electronic ablation of **nanoparticles**

Plasma expansion

Plume condensation

Harilal S.S. et al., in "Laser-induced breakdown spectroscopy", ch. 6, 2014

ns-PLD

- **Well-established**
- Better **thickness uniformity**
- Atom-by-atom deposition
- **Gas-mediated** nanoparticle synthesis

fs-PLD

- **Direct** nanoparticle synthesis
- High ablation efficiency
- Technically **challenging**
- Great flexibility in **material choice**

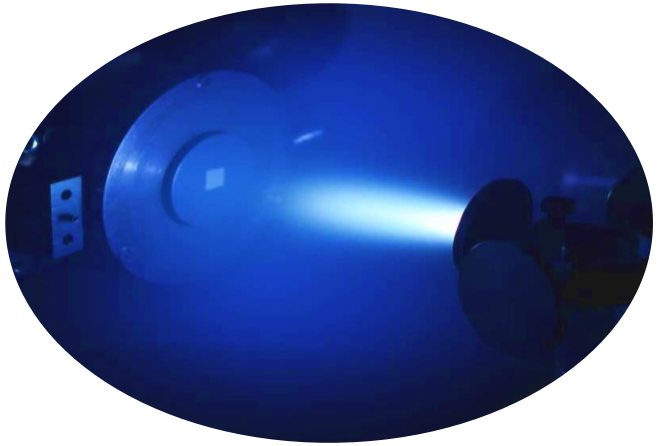
Outline and methods

1

Comparative investigation of carbon nanofoams through ns and fs-PLD

ns-PLD

fs-PLD

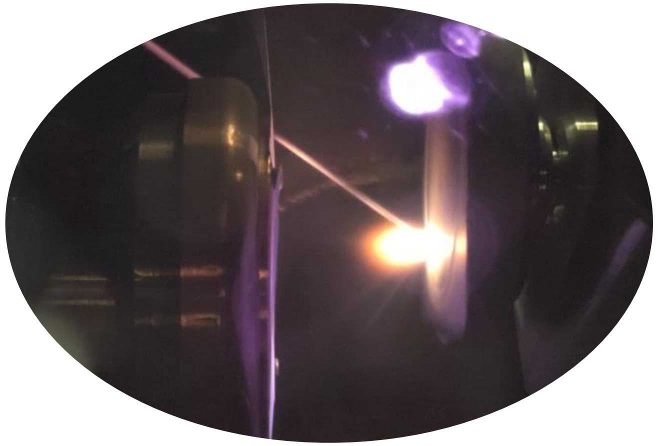


ns-PLD

- Nd:YAG (SH @ **532 nm**)
- **5 – 7 ns** pulse duration
- 100 – 600 mJ per pulse
- **100 – 600 mJ/cm²**
- 10 Hz

fs-PLD

- Ti:Sapphire (**800 nm**)
- **~80 fs** pulse duration
- 1 – 4 mJ per pulse
- **100 – 600 mJ/cm²**
- 1 kHz



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Outline and methods

1

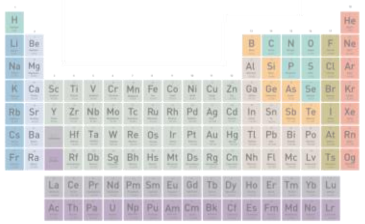
Comparative investigation of carbon nanofoams through ns and fs-PLD

ns-PLD

fs-PLD

2

fs-PLD synthesis of **different elements** nanofoams



Investigate the **deposition and growth** process

3

Development of **application-tailored** nanostructured materials

- Laser-driven **particle acceleration**
- Inertial confinement fusion (**ICF**)
- **Proton-boron** fusion

Bone tissue engineering (**BTE**)

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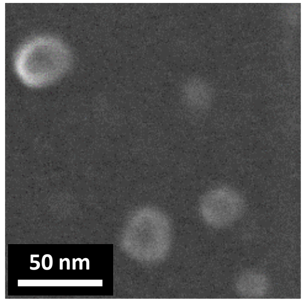
Carbon nanofoams

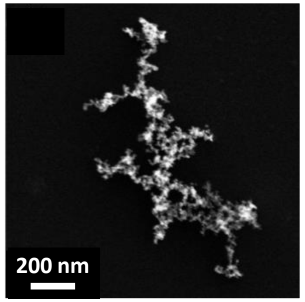


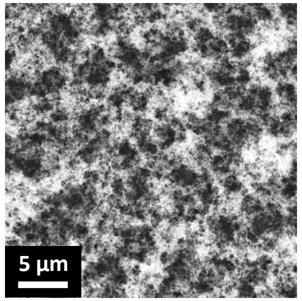
Nanoparticle production

1

2

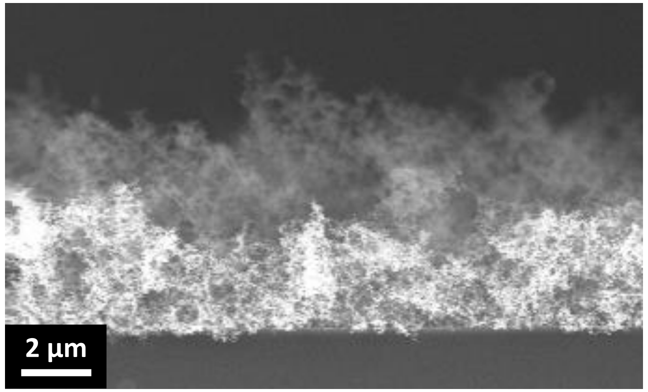
In-flight interaction and **fractal aggregate** formation





Deposition on the substrate and foam growth

3

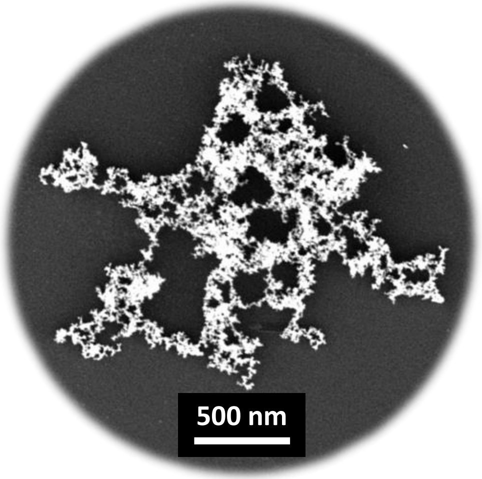


Average density and **morphology** investigation

ns-PLD

fs-PLD

Fractal aggregates study



Argon **background pressure**

Maffini A. et al., Physical Review Materials 3.8, 2019

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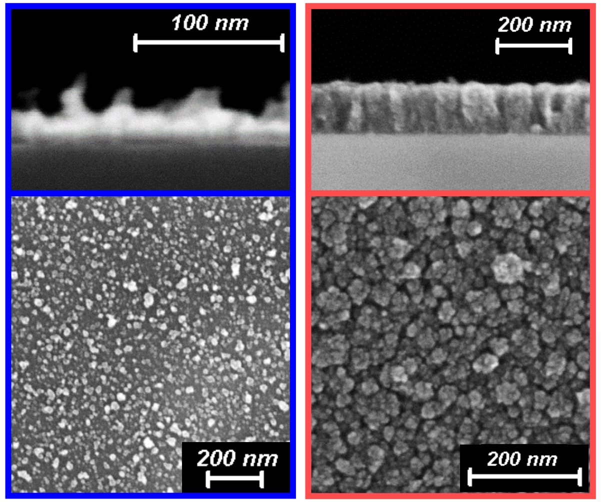
Carbon nanofoams

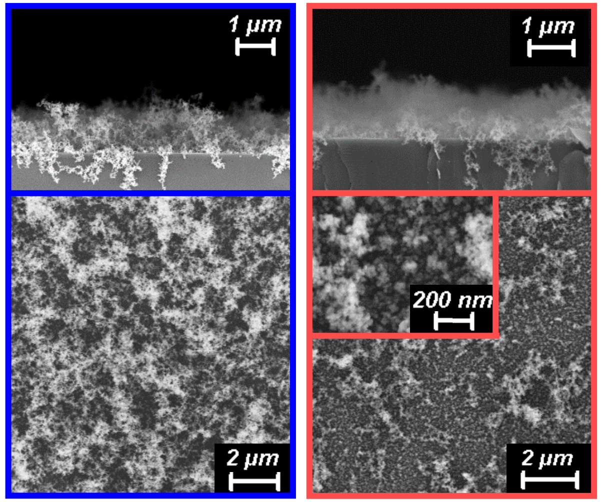
Density and morphology

Mixed morphology
for fs-PLD

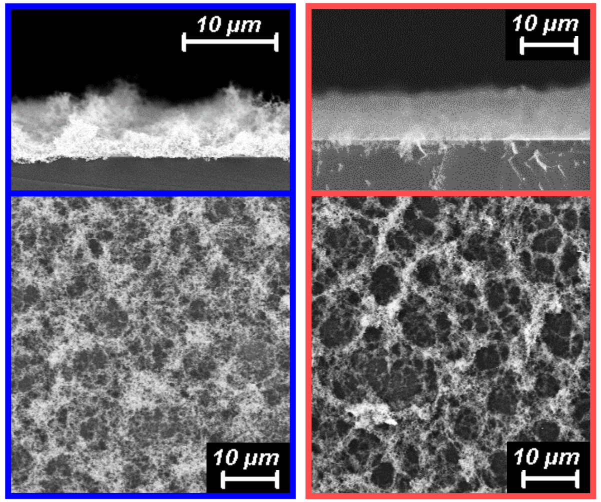
25 Pa



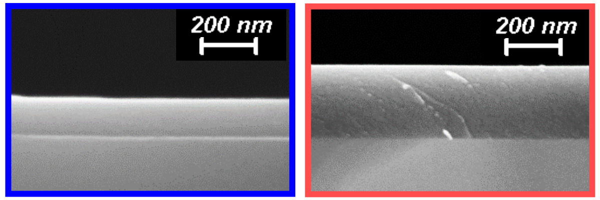
50 Pa

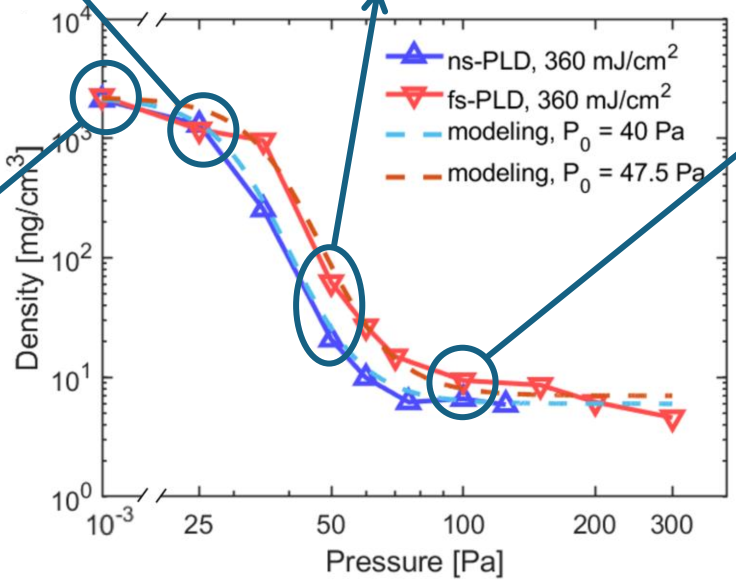


100 Pa



< 10^{-3} Pa





Analogous density
evolution

Maffini A. et al., Appl. Surf. Sci., 2022

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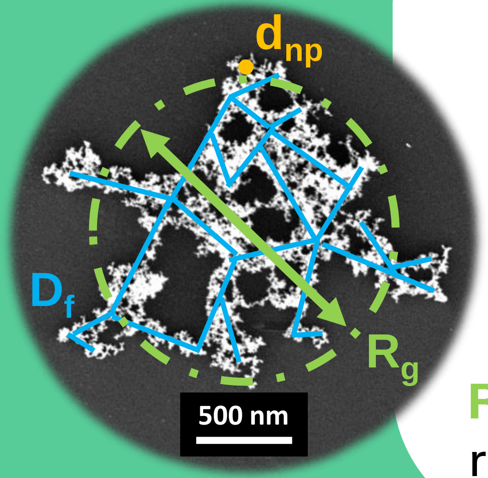
Fractal aggregate study



d_{np} nano-particle size

D_f fractal dimension

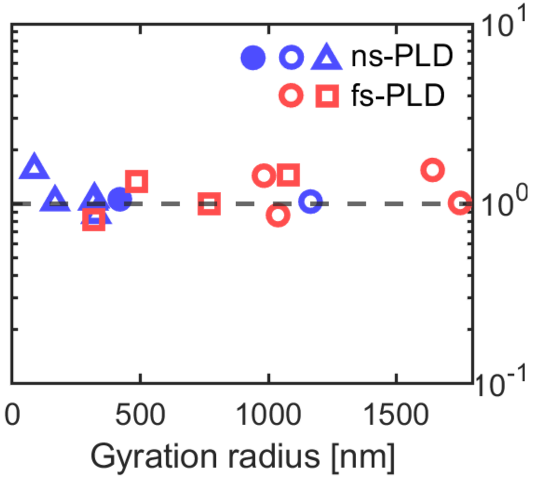
R_g gyration radius

$$\rho_{th} \cong k\rho_{np}\left(\frac{d_{np}}{2R_g}\right)^{3-D_f}$$

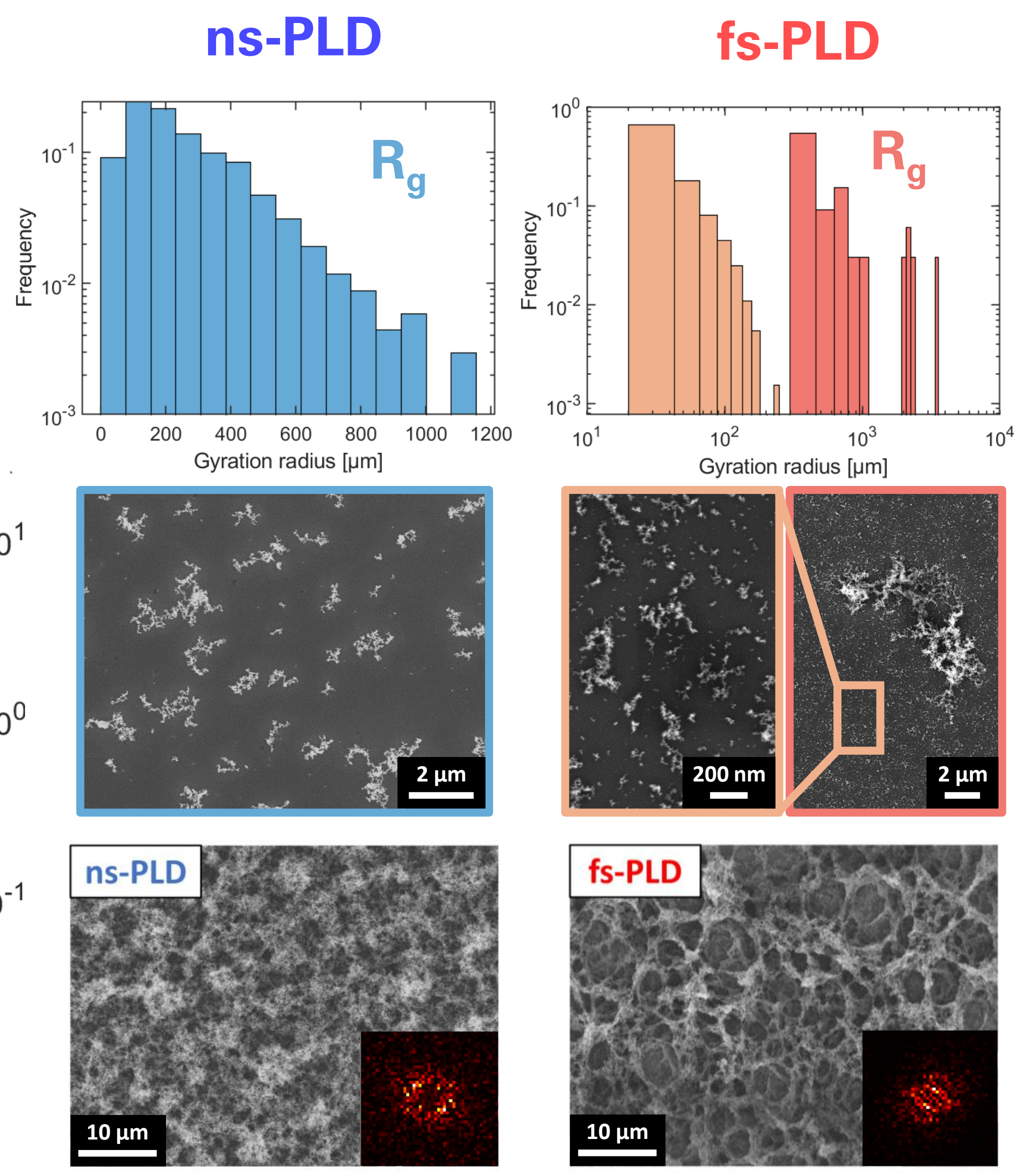
$d_{np} \approx$ 8 nm / 10 nm

$D_f \approx 2$ in all conditions

ρ_{th}/ρ_{exp}



Great **agreement**



Maffini A. et al., Appl. Surf. Sci., 2022

Carbon nanofoams

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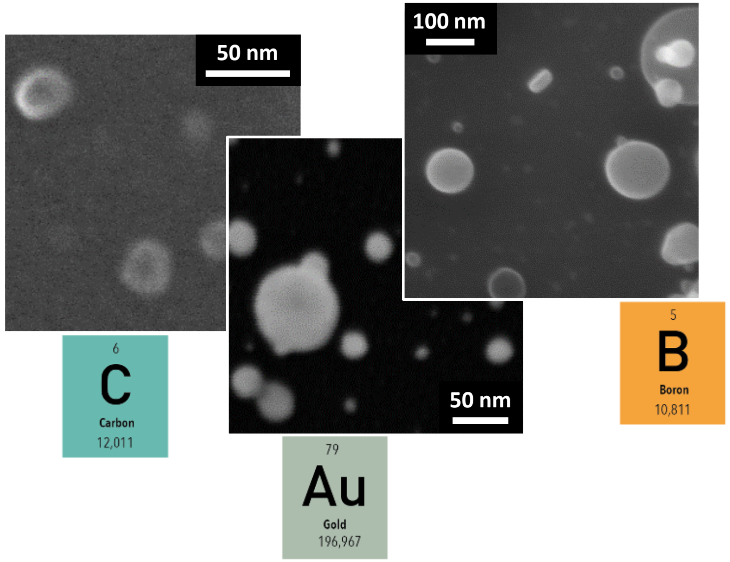
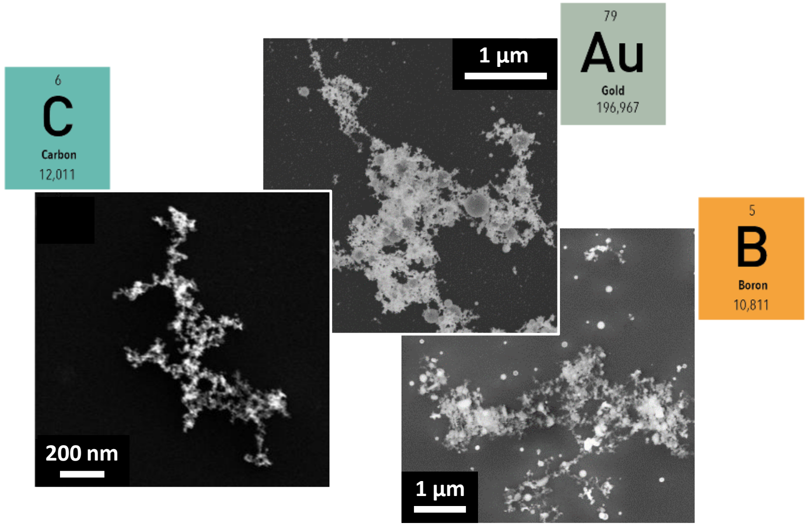
fs-PLD nanofoams synthesis

fs-PLD ⟳ ns-PLD

1

Nanoparticle production



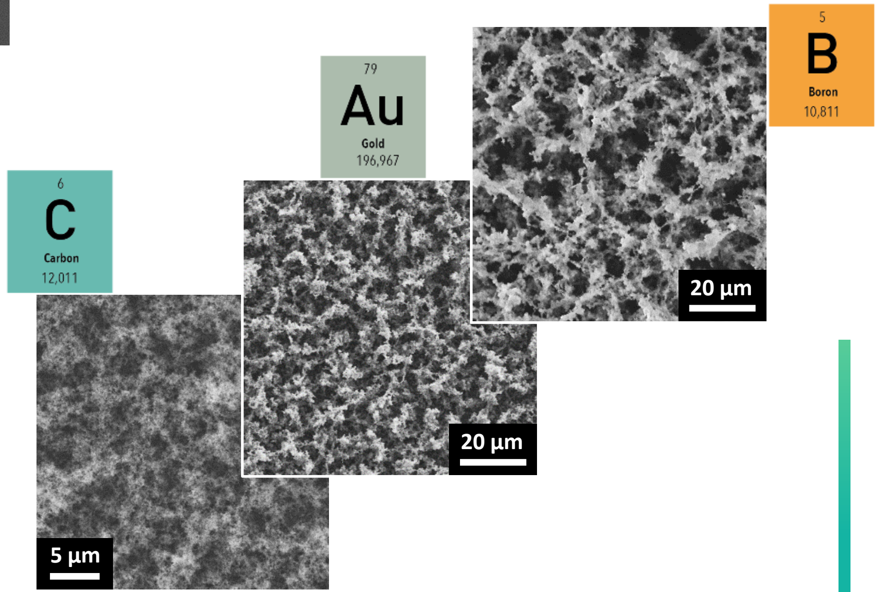


In-flight interaction and **fractal aggregate** formation

2

3

Deposition on the substrate and foam growth



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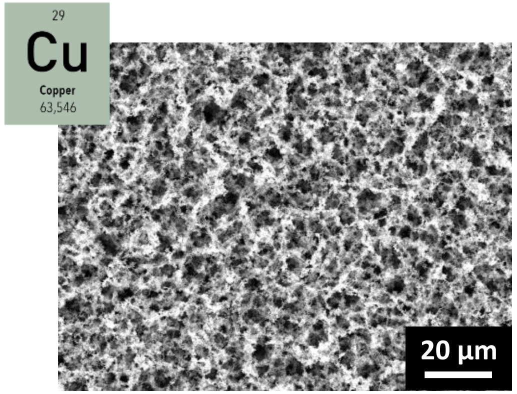
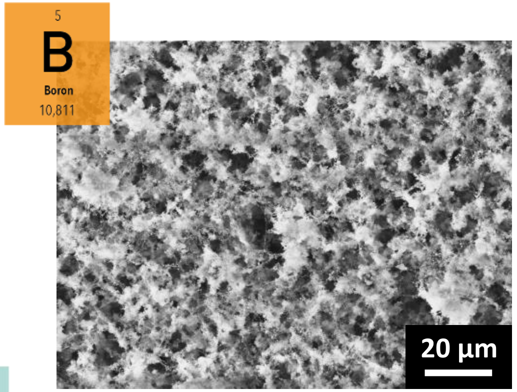
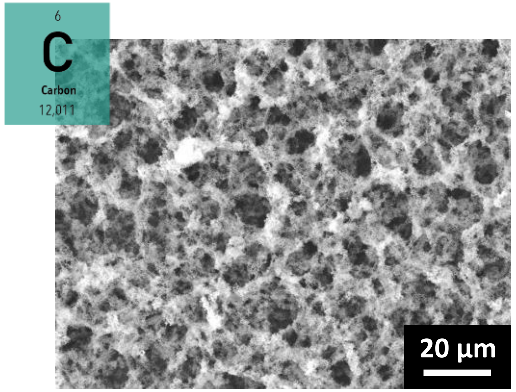
fs-PLD nanofoams

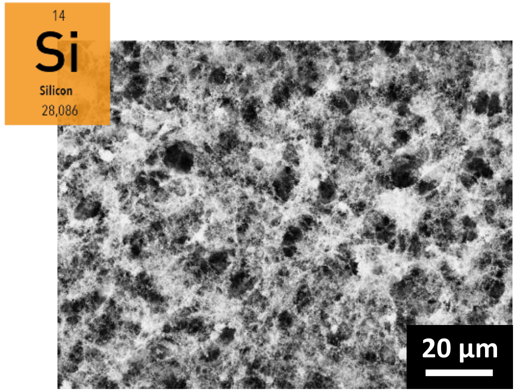
Versatile nanofoam production through fs-PLD

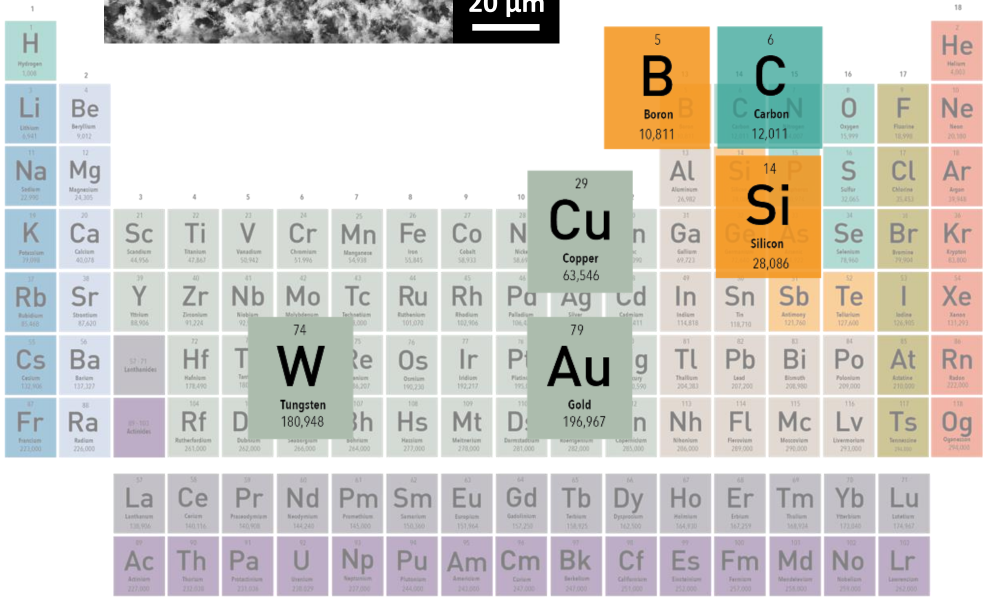


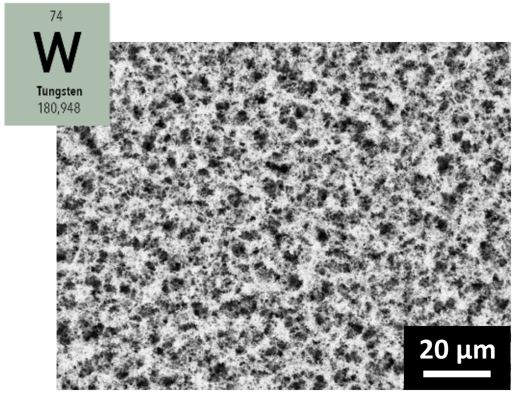


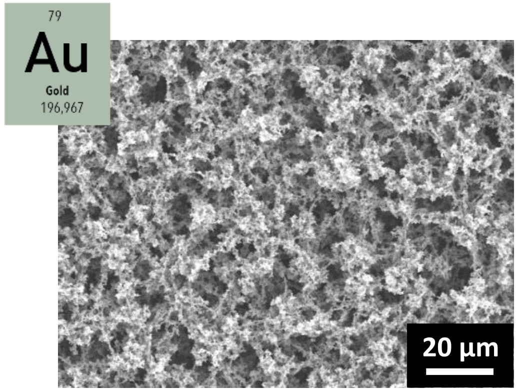


Analogous morphology









Same **ablation fluence** $\sim 0.1\ \text{J/cm}^2$

Orecchia D. et al., *Small Structures* 5, 2024

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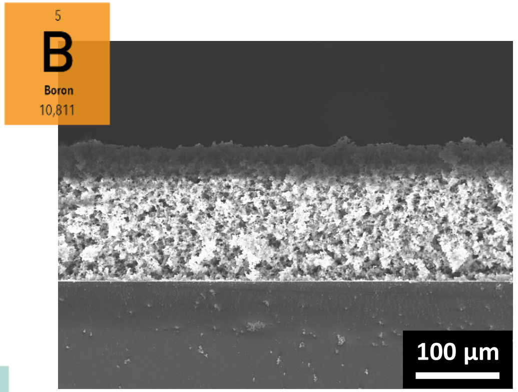
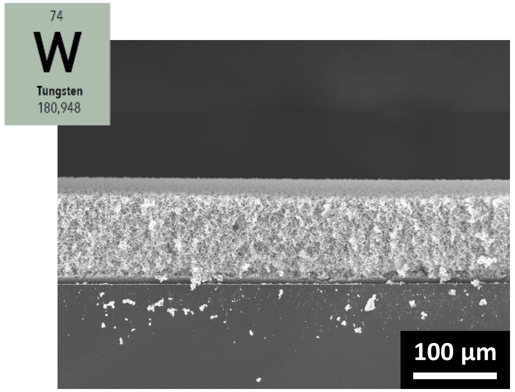
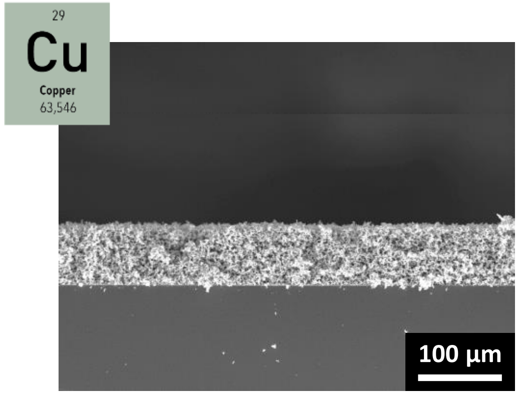
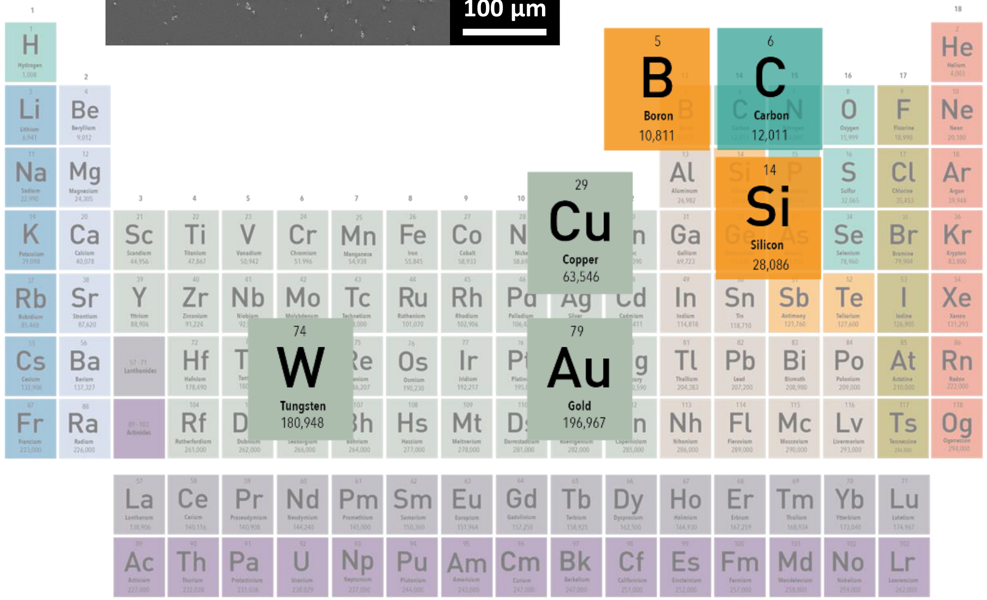
fs-PLD nanofoams

Versatile nanofoam production through fs-PLD

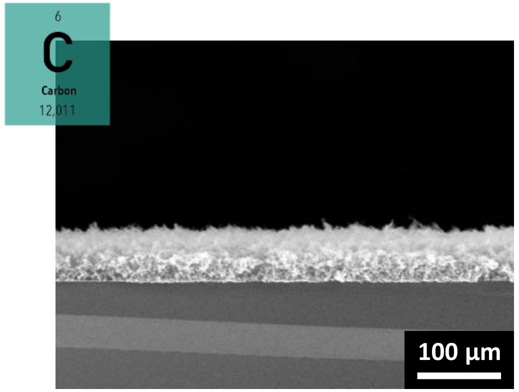


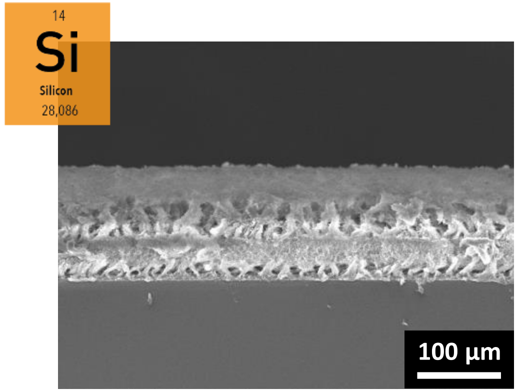


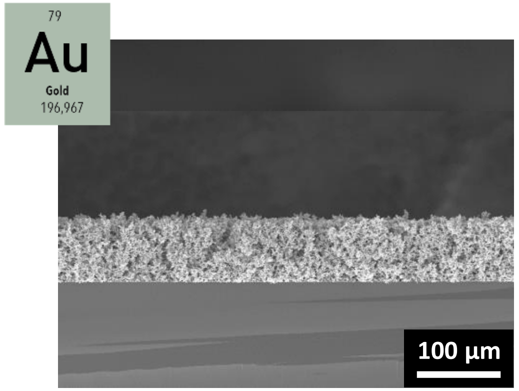




Analogous morphology







Same **ablation fluence** $\sim 0.1\ \mathrm{J/cm^2}$

Exceeding **100 µm** thickness

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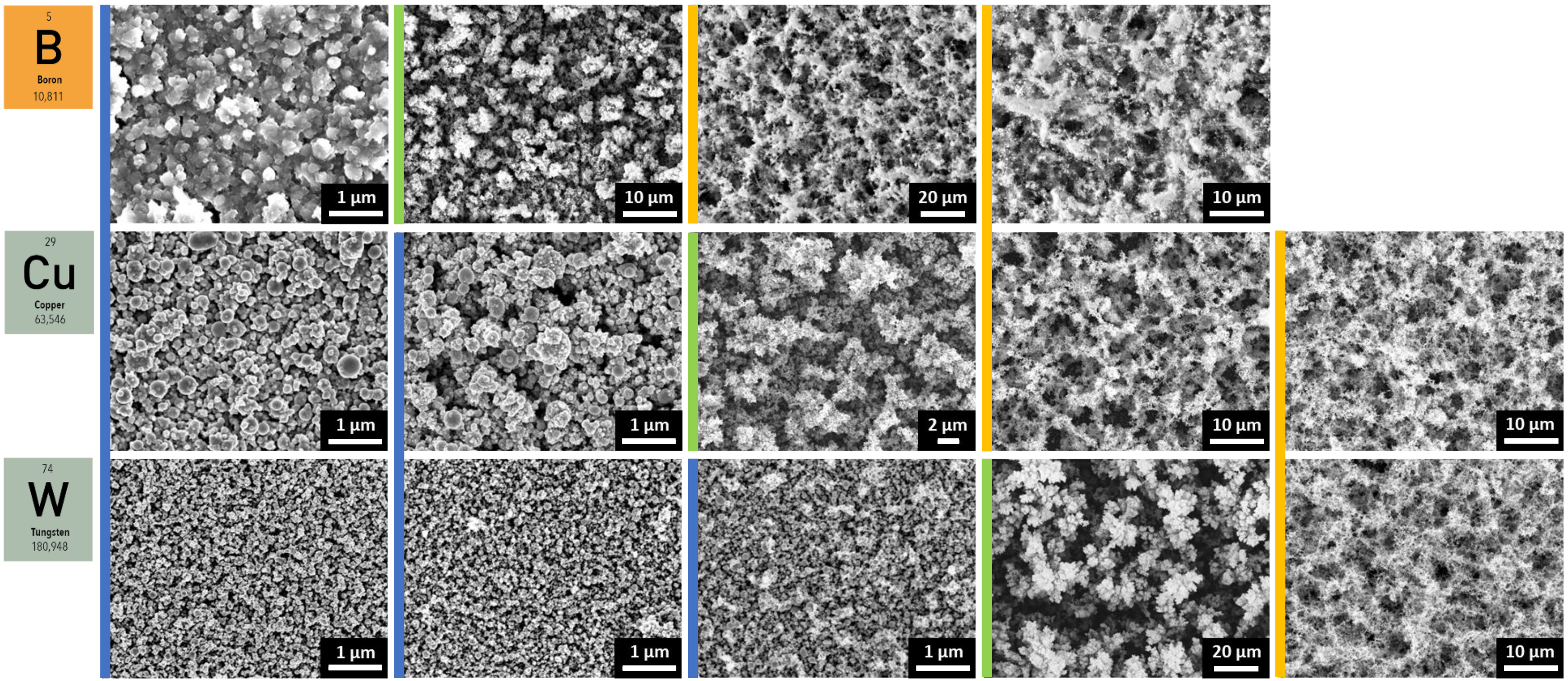
Orecchia D. et al., Small Structures 5, 2024

Morphology and gas pressure

Argon gas **pressure** →

10^{-3} Pa | 100 Pa | 400 Pa | 1000 Pa | 5000 Pa



Same morphology evolution

Different pressure thresholds

Nanoparticle-assembled compact film → **Tree-like** nanostructured film → Web-like **nanofoam**

Orecchia D. et al., Small Structures 5, 2024

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fs-PLD nanofoams

Average density and gas pressure

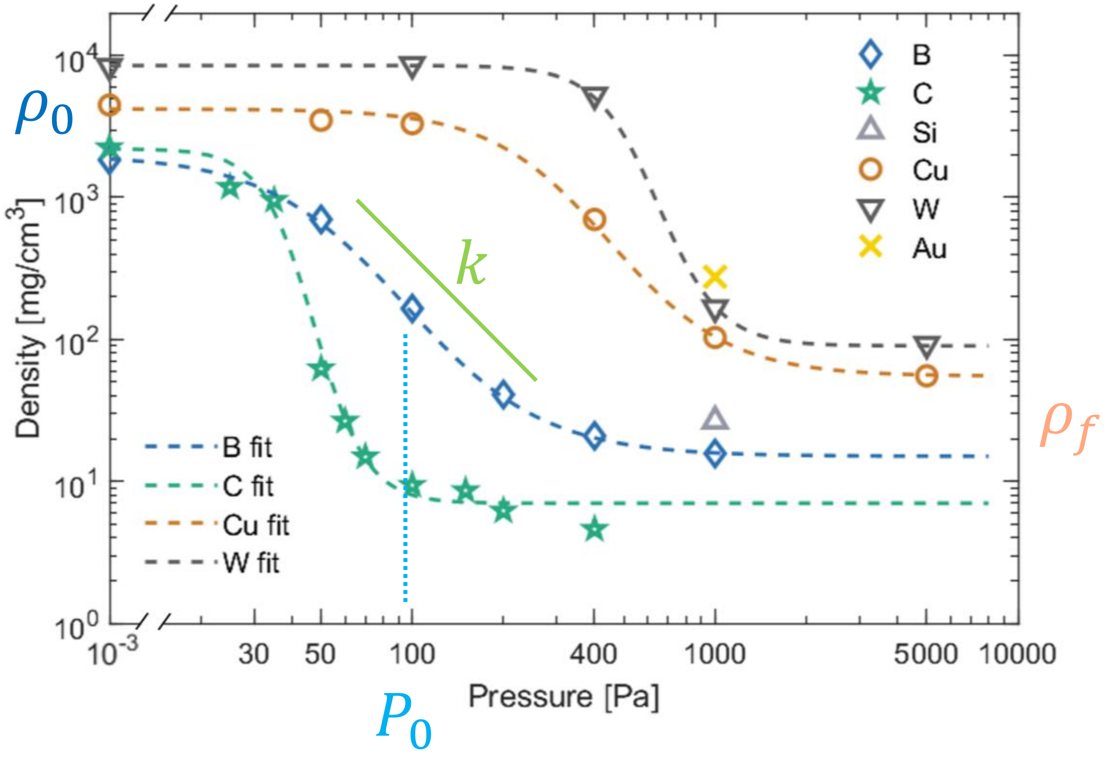
$$\rho(P) = \rho_0 \left(\frac{\rho_f}{\rho_0}\right)^{\left[\frac{P^k}{P^k + P_0^k}\right]}$$

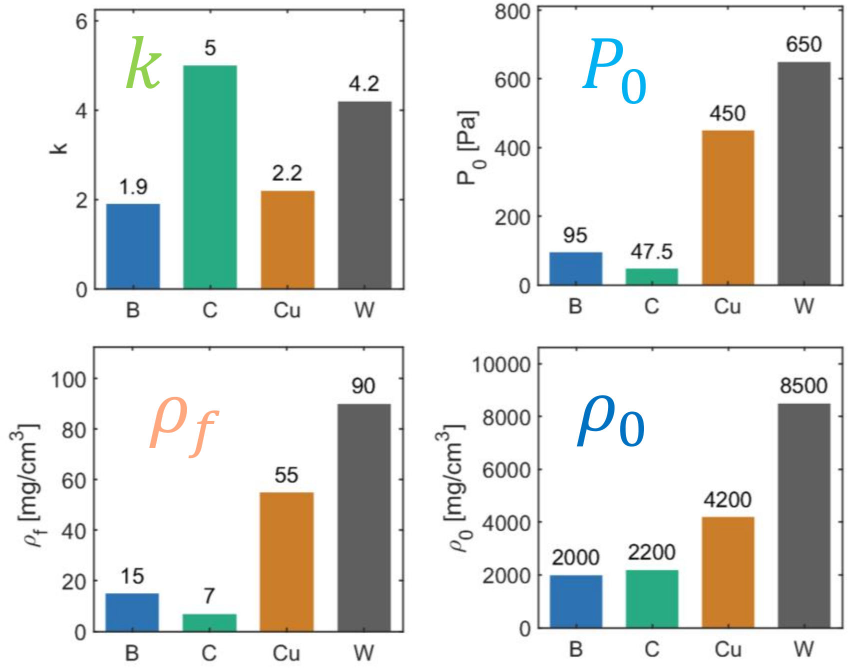
$$\gamma \propto \frac{P}{R\rho v_t}$$

$$\dot{v} = -\gamma v$$

Relative **slowing efficiency** of the background gas

Dimension, **energetics** and **density** of ablated nanoparticles





Nanofoam **average density** and **morphology**

Orecchia D. et al., Small Structures 5, 2024

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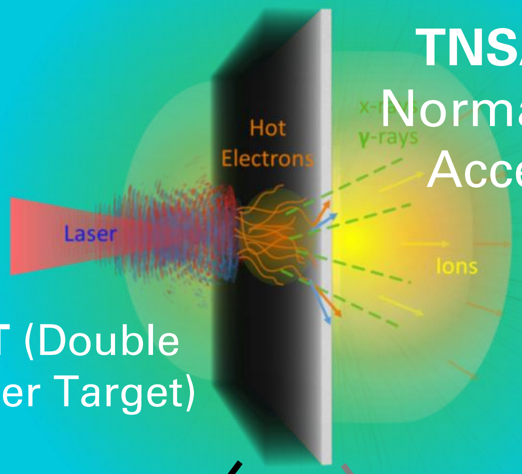
fs-PLD nanofoams

Laser-driven particle acceleration



TNSA (Target Normal Sheath Acceleration)

DLT (Double Layer Target)

Near-critical **carbon nanofoam**

- $\sim 6\ \mathrm{mg/cm^3}$
- $9 - 54\ \mu\mathrm{m}$

Micrometric **solid Al substrate**

- solid density
- $0.75 - 13\ \mu\mathrm{m}$

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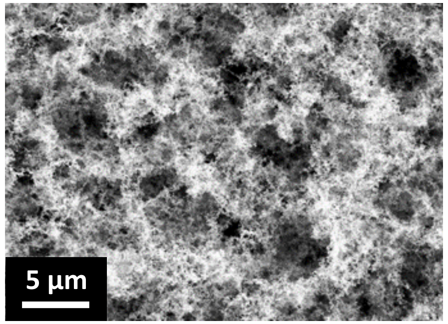
VEGA 3

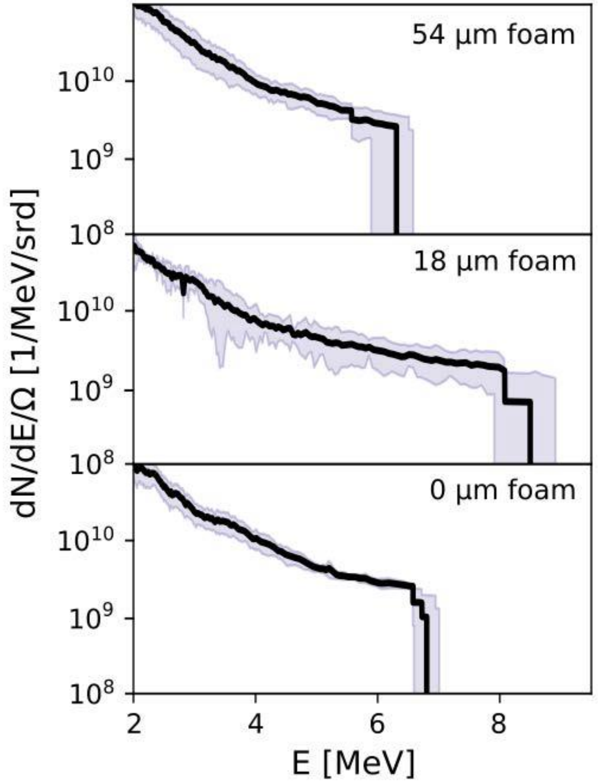
CLPU CENTRO DE LÁSERES PULSADOS

- **20 J**
- **30 fs**
- $\lambda = 800$ **nm**
- 12 μm spot size
- **10^{20} W/cm²**
- 5×10^{-12} contrast



Low-density **carbon nanofoam**

Proton **spectrum**



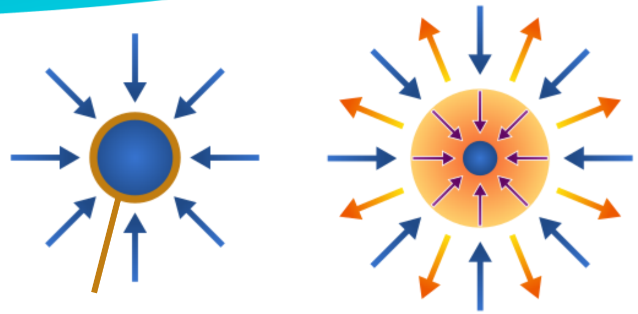
Proton energy **enhancement** in DLTs

High-intensity laser applications

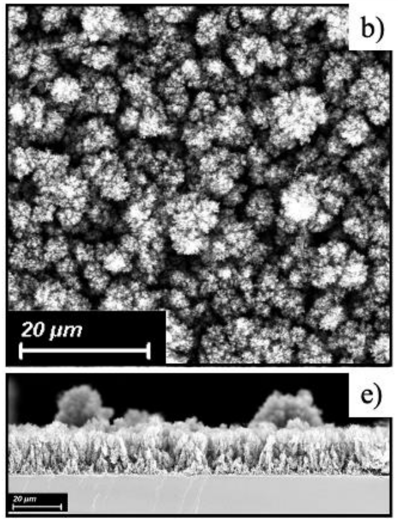
Carbon nanofoams as inertial confinement fusion ablator

ABC

- **40 J**
- **3 ns**
- $\lambda = 1054$ **nm**
- 100 μm spot size
- **10^{14}-10^{15} W/cm^2**



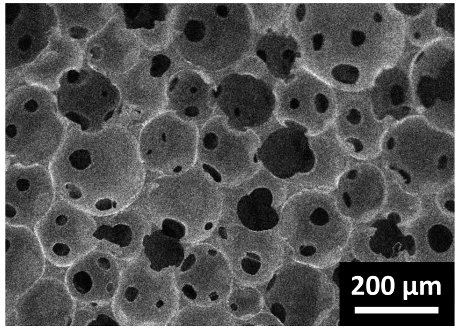
Ablator



Significant **ablation loading** increase in **tree-like** films

1

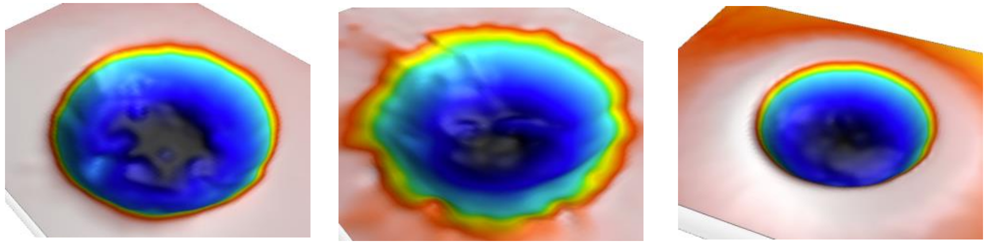
Laser **absorption enhancement**



2

Laser **inhomogeneity smoothing**

Foam on Al | Treelike on Al | Bare Al



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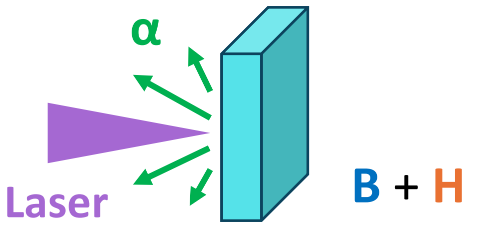
ENEA

High-intensity laser applications

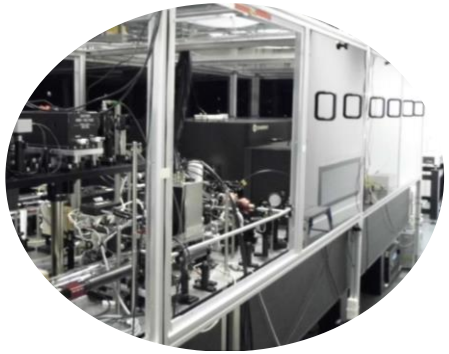
Boron nanofoams for proton-boron fusion

$p + {}^{11}B \rightarrow 3\alpha + E$

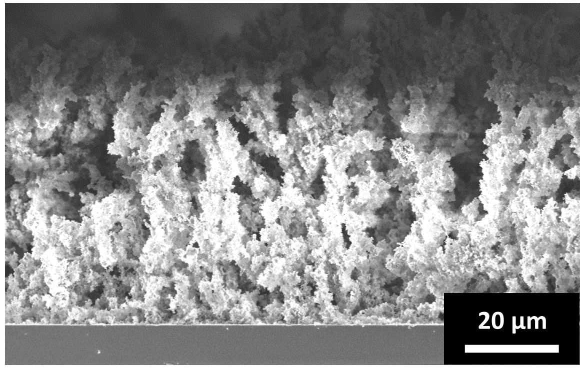


Hydrogen-enriched boron nanofoams

TARANIS



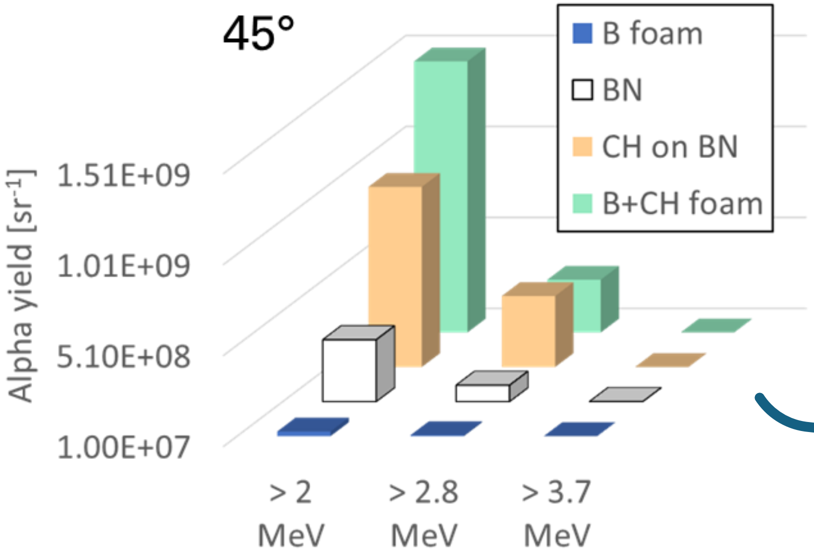
- **10 J**
- **800 fs**
- $\lambda = 1053$ **nm**
- 5.5 µm spot size
- **10^{19} W/cm²**
- 5×10^{-7} contrast



fs-PLD **codeposition** with a **boron/HDPE** target

H/B ratio of **1.5**

20% C, 10% O



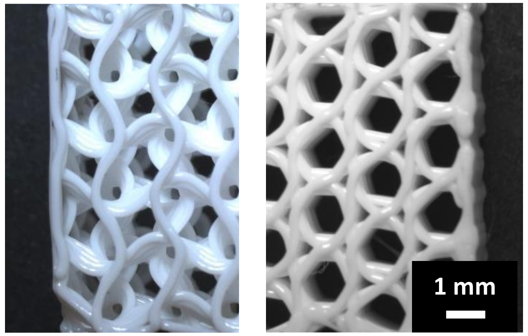
Substantial alpha yield **enhancement**

High-intensity laser applications

Nanostructured hydroxyapatite coating for BTE

(Bone Tissue Engineering)

Mimic different bone tissues



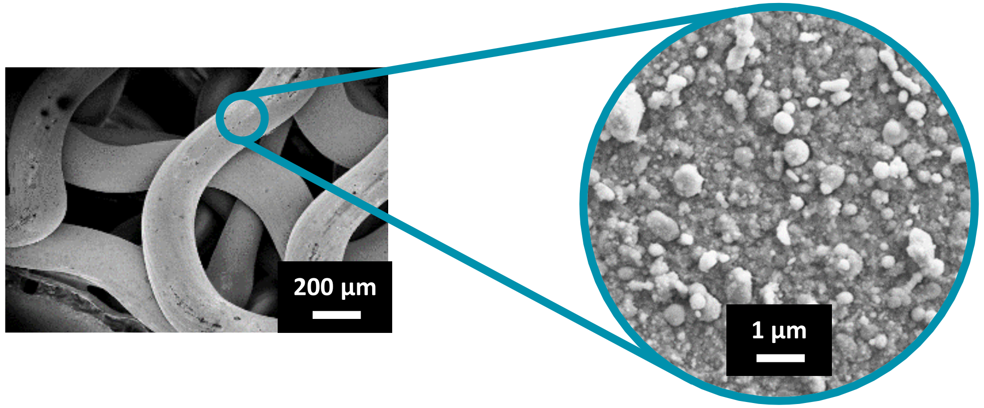
3D printed PLA **scaffold**

Roughness, **morphology** and chemical **composition** control

fs-PLD of **bovine bone** target

Stoichiometric transfer *+ trace elements*

Promising 10 days **stability** in phosphate buffered saline solution



Biogenic hydroxyapatite **nanostructured** coating

Bone cells growth investigation **planned**

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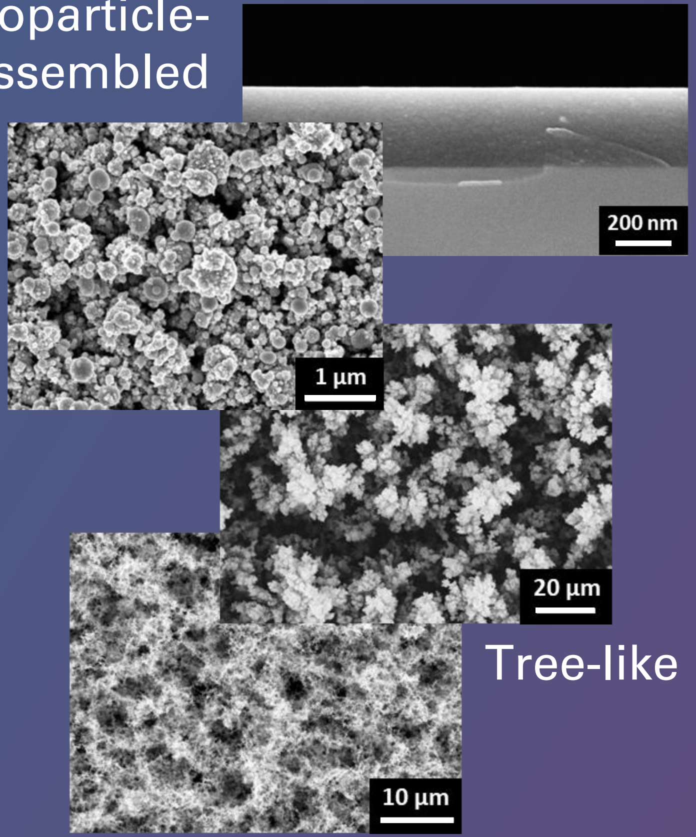
Bone tissue engineering

Conclusions

Compact

Nanoparticle-assembled



Tree-like

Nanofoam

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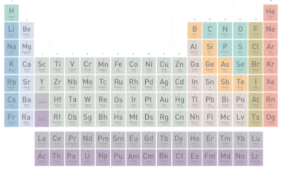

Dimension, **energetics** and **density** of ablated nanoparticles

Nanofoam **properties**

Relative **slowing efficiency** of the background gas

ns-PLD and fs-PLD are **complementary** and **versatile** techniques

Laser coupling enhancement

- Laser-driven **particle energy**
- ICF **ablation loading**
- **Proton-boron** fusion yield

Material **properties**

Application **requirements**

Promising nanostructured coating for **BTE**

Conclusions

NanoLab

Thank you for your attention!

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