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Femtosecond pulsed laser deposition of low density nanofoams

Orecchia D., *Maffini A., Zavelani-Rossi M., Passoni M.*

NanoLab

EUROfusion

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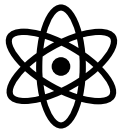
Overview

Introduction: nanofoams

Pulsed Laser Deposition (PLD)

Nanofoam production with femtosecond-PLD

Morphological and average density analysis

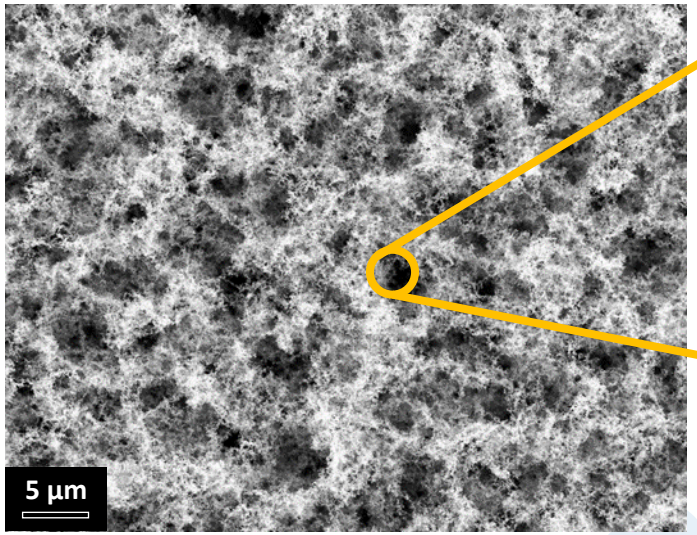


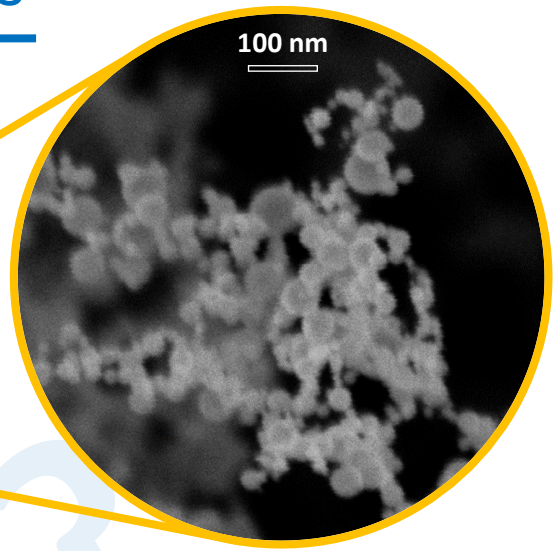
Target applications

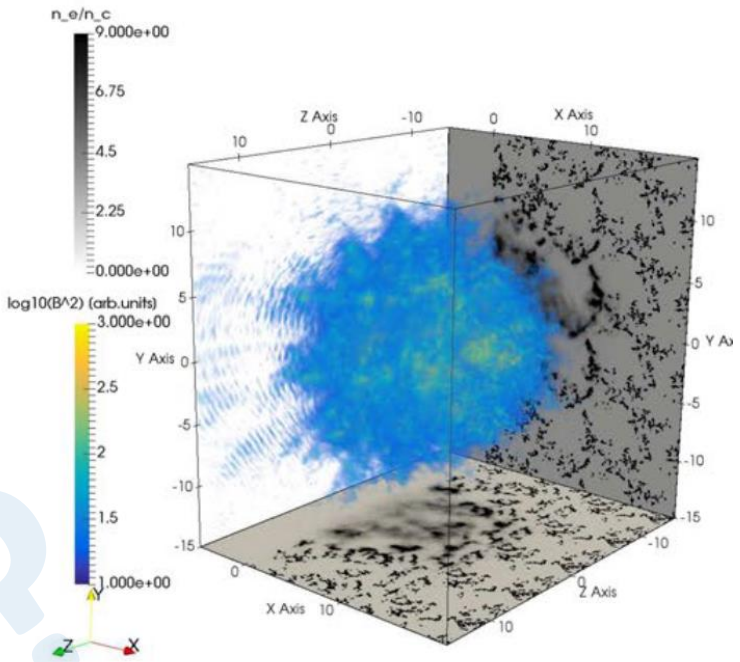
Conclusion and perspectives

Introduction: nanofoams

adapted from Fedeli L. et al., Scientific reports 8.1, 2018







- **Nanoparticle**-assembled web-like structures
- High **surface area**
- Down to **few mg/cm³** density (high void fraction)

Chemistry

- Catalysis
- Supercapacitors

Laser-matter interaction

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

Efficient laser energy absorption

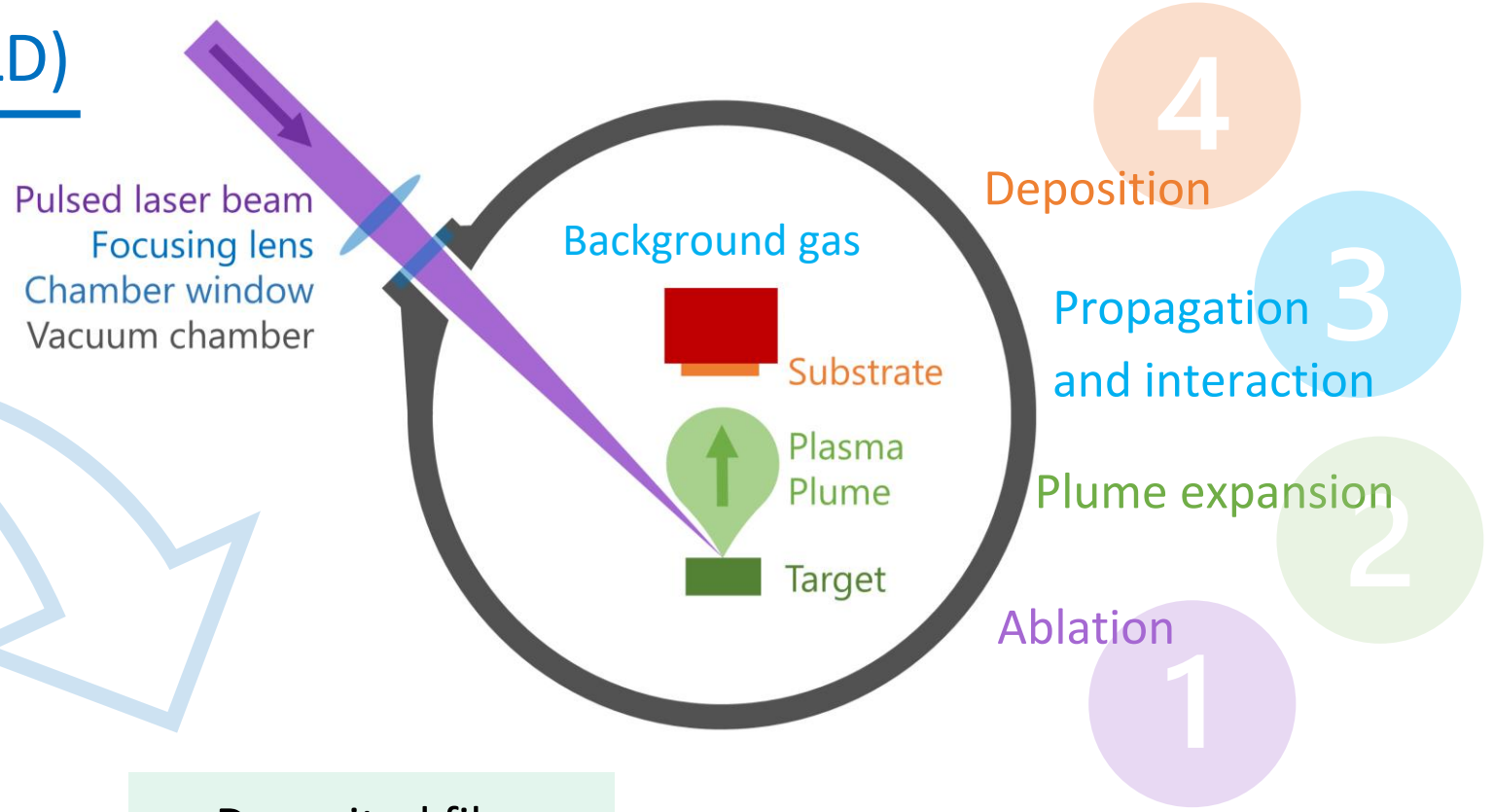
Volumetric interaction

What? Why?

Pulsed Laser Deposition (PLD)

Process parameters

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



Laser **pulse duration**

ns-PLD

- Well established
- Few ns pulses
- 100s mJ per pulse
- Up to 10 Hz

fs-PLD

- Nonstandard
- <100 fs pulses
- Few mJ per pulse
- kHz or higher

Deposited film **properties control**

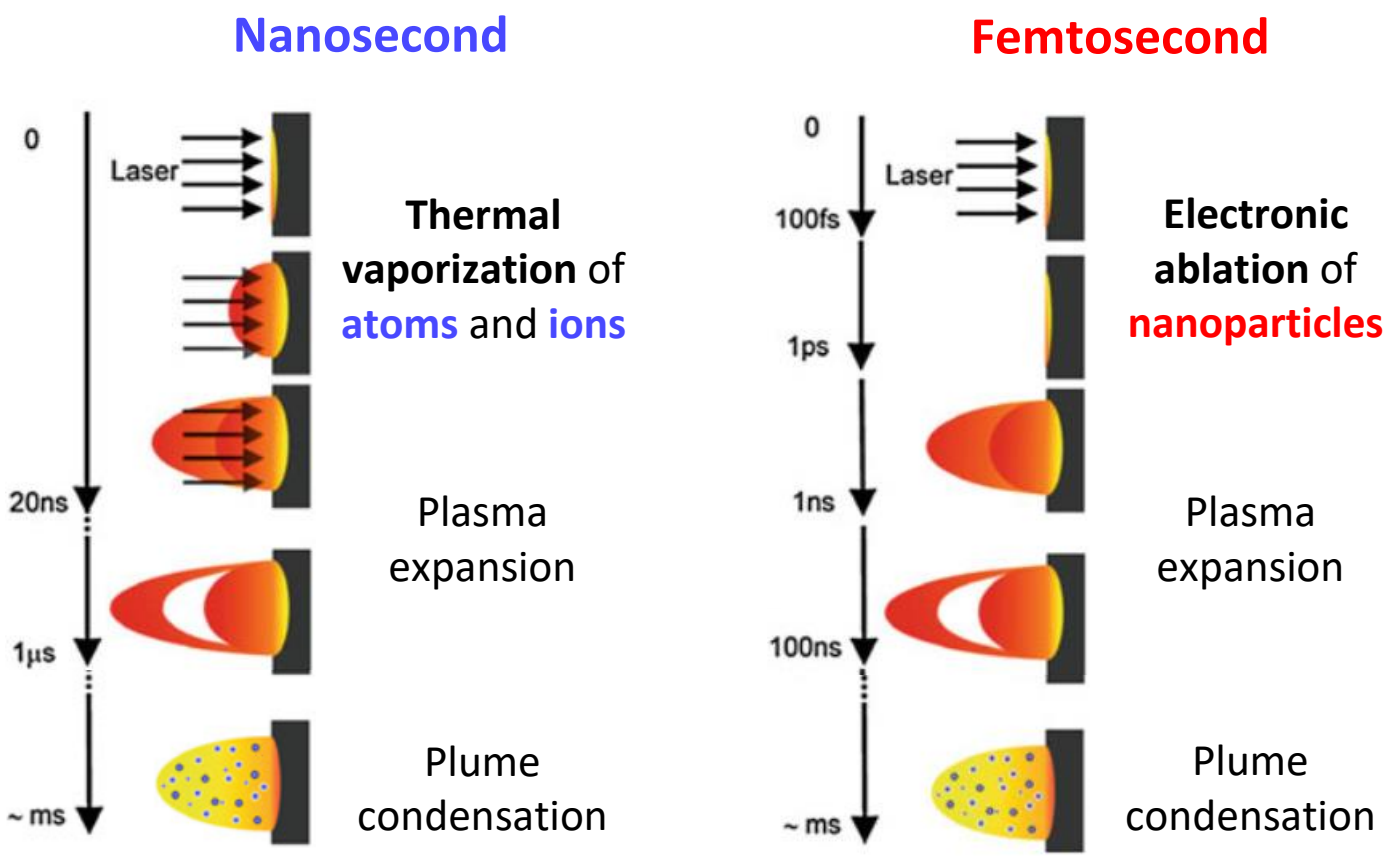
(density, thickness, elemental composition)

Flexible technique

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

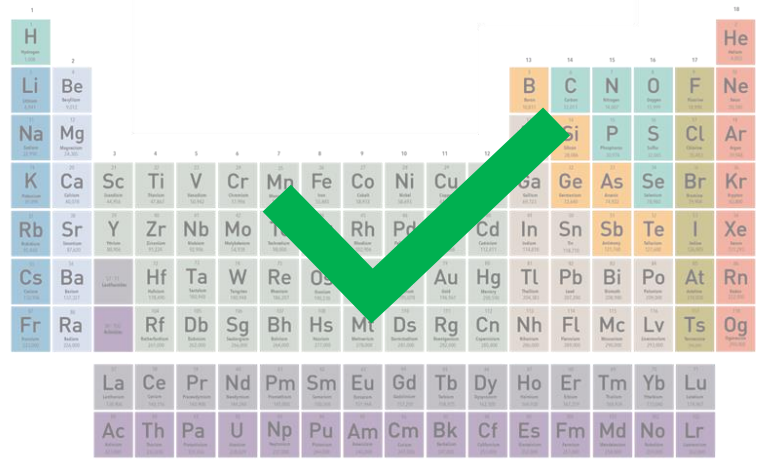
Why femtosecond-PLD

Different ablation regimes

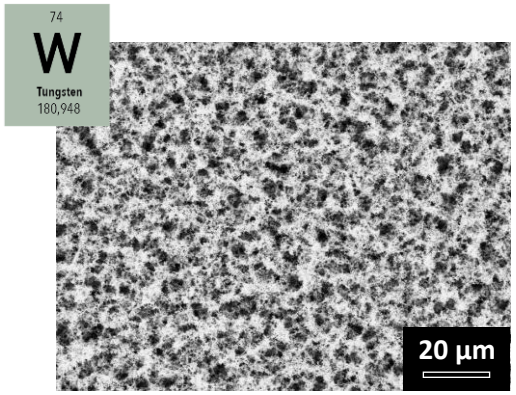


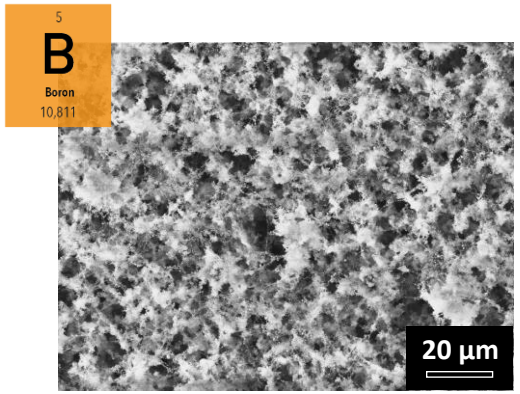
adapted from Harilal S.S. et al., in "Laser-induced breakdown spectroscopy", ch. 6, 2014

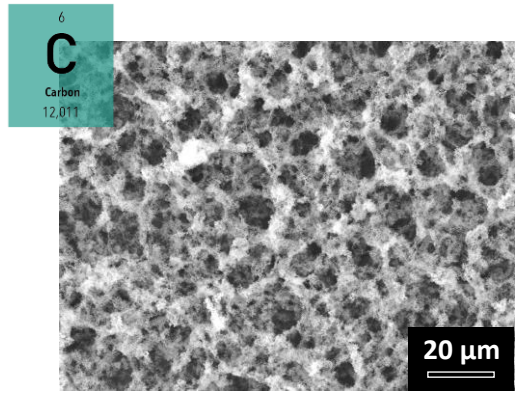
- Direct **nanoparticle** production
- Not suitable for compact films
- High deposition rate
- Technically **challenging**
- Great flexibility in **material choice**



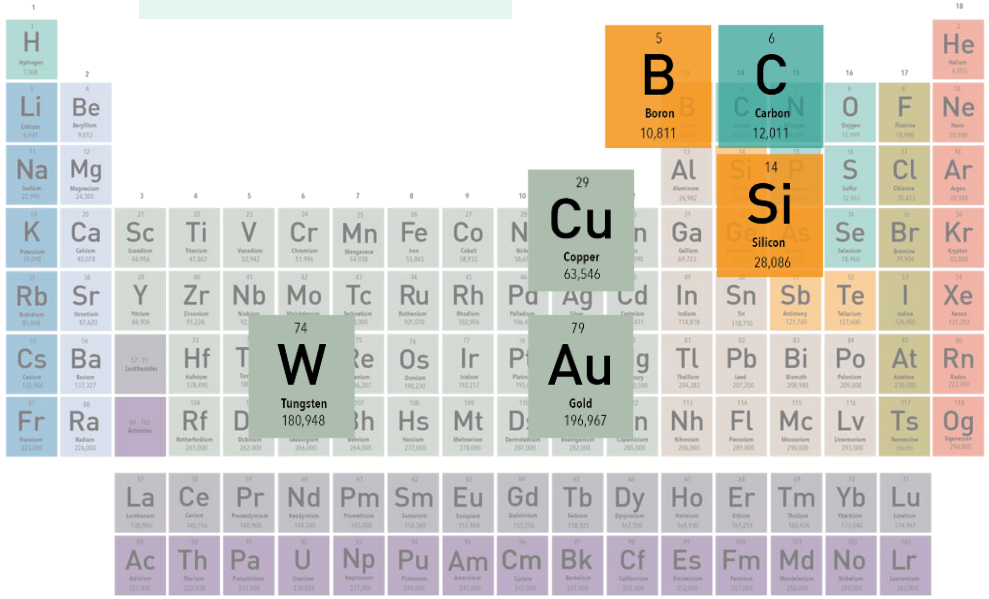
Nanofoams production with fs-PLD

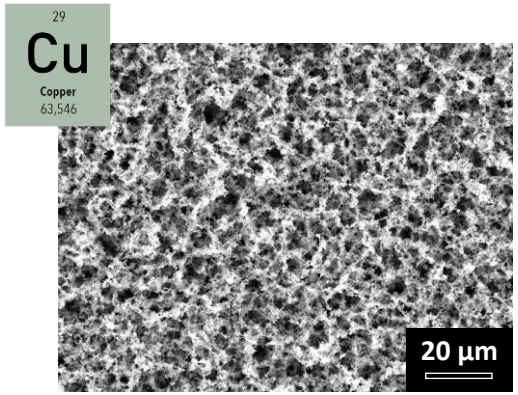


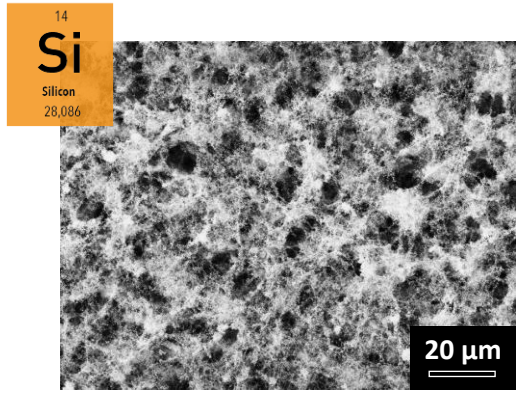


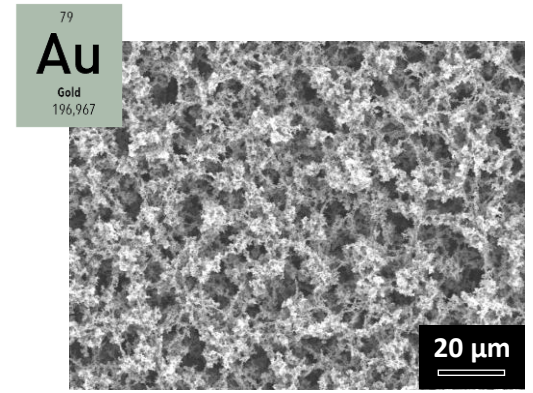


Analogous morphology









Article in preparation: "Femtosecond pulsed laser deposition of cluster-assembled nanofoams"

Elements with **different properties** + **Same laser fluence** ($\sim 0.1\ J/cm^2$)

Nanofoams aggregation mechanism

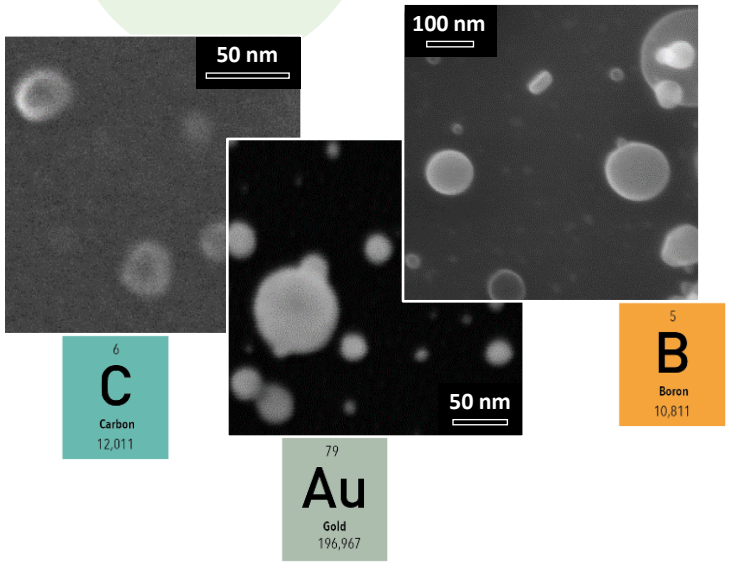
Maffini A. et al., Physical Review Materials 3.8, 2019

Maffini A. et al., Applied Surface Science 599, 2022

C Carbon 12,011 — Well investigated

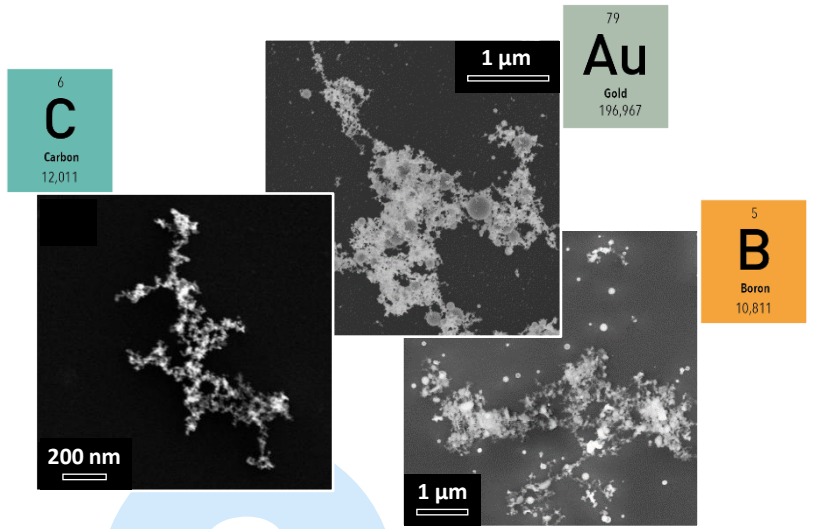
Nanoparticle production

1

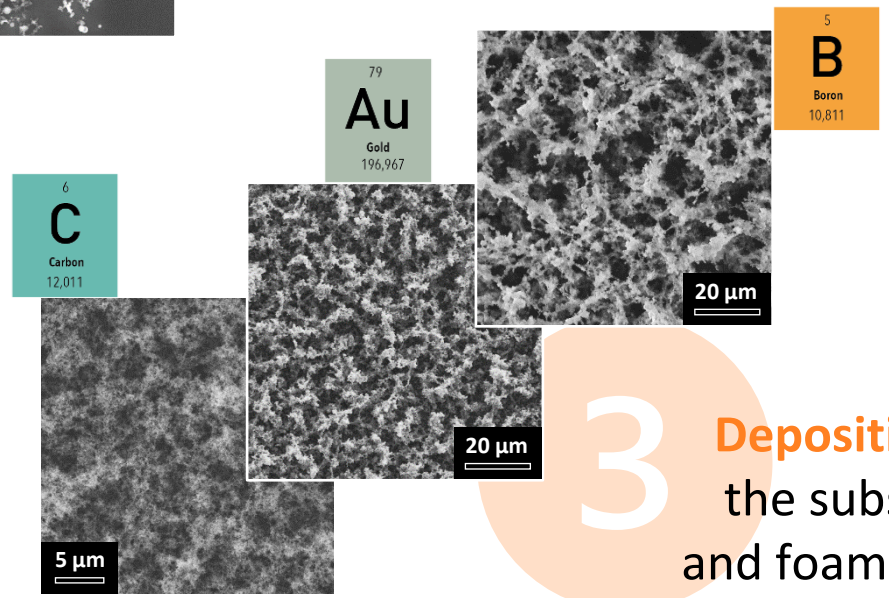


2

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



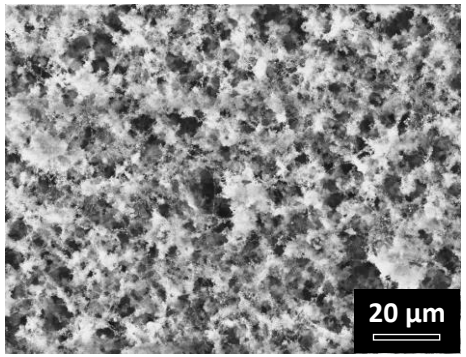
W Si Cu Au B — **Same** general **behavior**



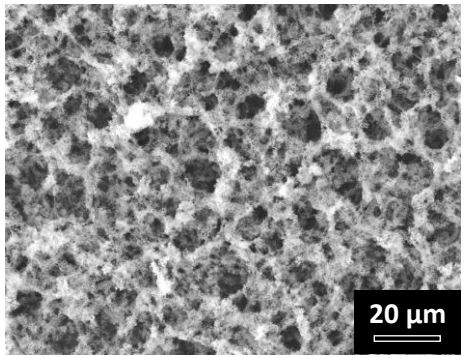
3

Deposition on the substrate and foam growth

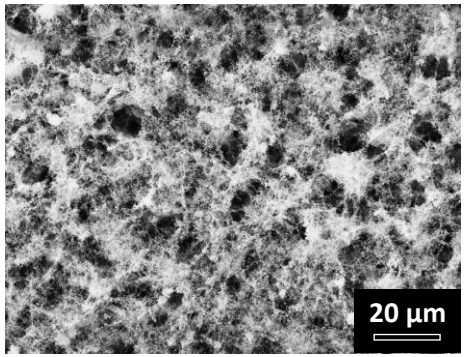
fs-PLD nanofoams properties



5 B Boron 10,811 — 400 Pa



6 C Carbon 12,011 — 400 Pa



14 Si Silicon 28,086 — 1000 Pa

Nanofoam properties

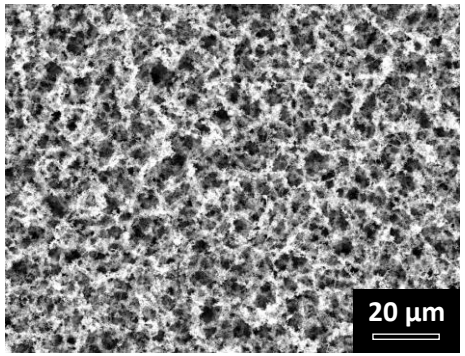
- Low average density, down to $\sim 15\ \mathrm{mg/cm^3}$
- $10\ \mu\mathrm{m} - \sim 100\ \mu\mathrm{m}$ thickness
- Non negligible ($\sim 5 - 20\%$) oxygen content
- Uniformity scale of $\sim 5 - 10\ \mu\mathrm{m}$

Argon gas **pressure** →

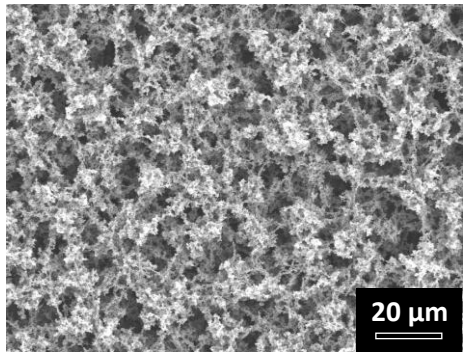
Deposition parameters

- **fs-PLD** ($800\ \mathrm{nm}$, $80\ \mathrm{fs}$, $1\ \mathrm{kHz}$)
- Background argon gas pressure ($100s - 1000s\ \mathrm{Pa}$)
- Constant fluence ($\sim 0.1\ \mathrm{J/cm^2}$)
- Low target-substrate distance ($\sim 3\ \mathrm{cm}$)

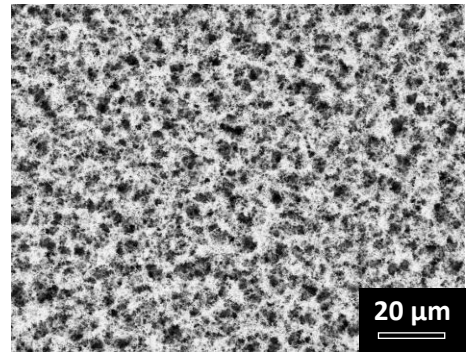
1000 Pa — 29 Cu Copper 63,546



1000 Pa — 79 Au Gold 196,967

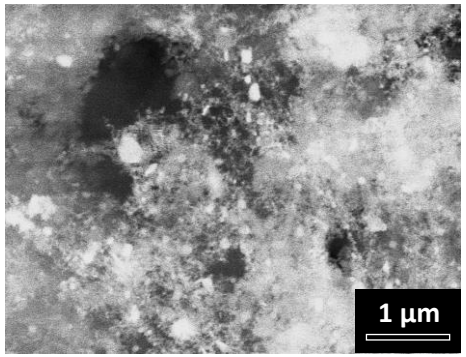


5000 Pa — 74 W Tungsten 180,948

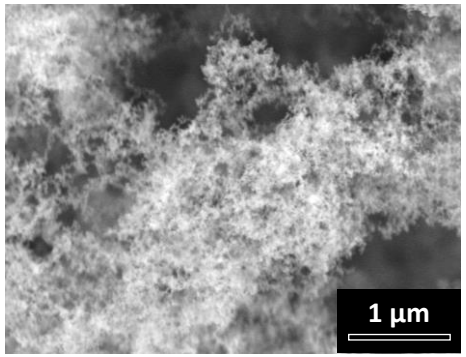


Nanostructure differences

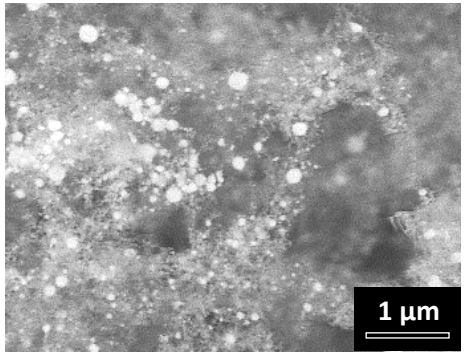
Dimensions, **energetics** and **concentration** of the ablated species



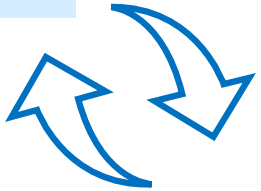
5 B Boron 10,811 — 400 Pa



6 C Carbon 12,011 — 400 Pa



14 Si Silicon 28,086 — 1000 Pa



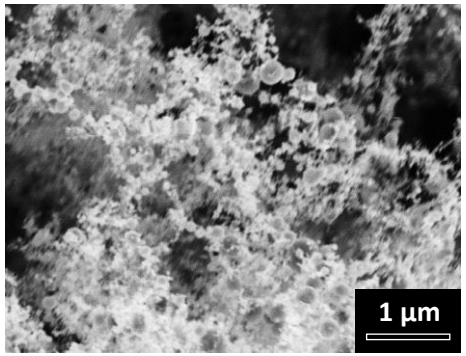
Relative **slowing efficiency** of the background gas

Argon gas **pressure**

Smaller nanoparticles ($\sim 10 - 20$ nm)

Larger nanoparticles (up to $\sim 100s$ nm)

1000 Pa — 29 Cu Copper 63,546



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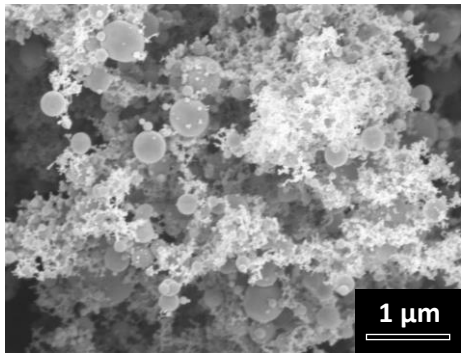

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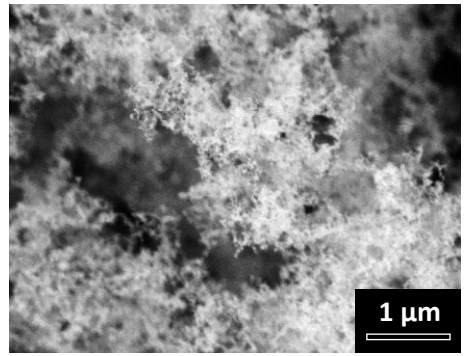


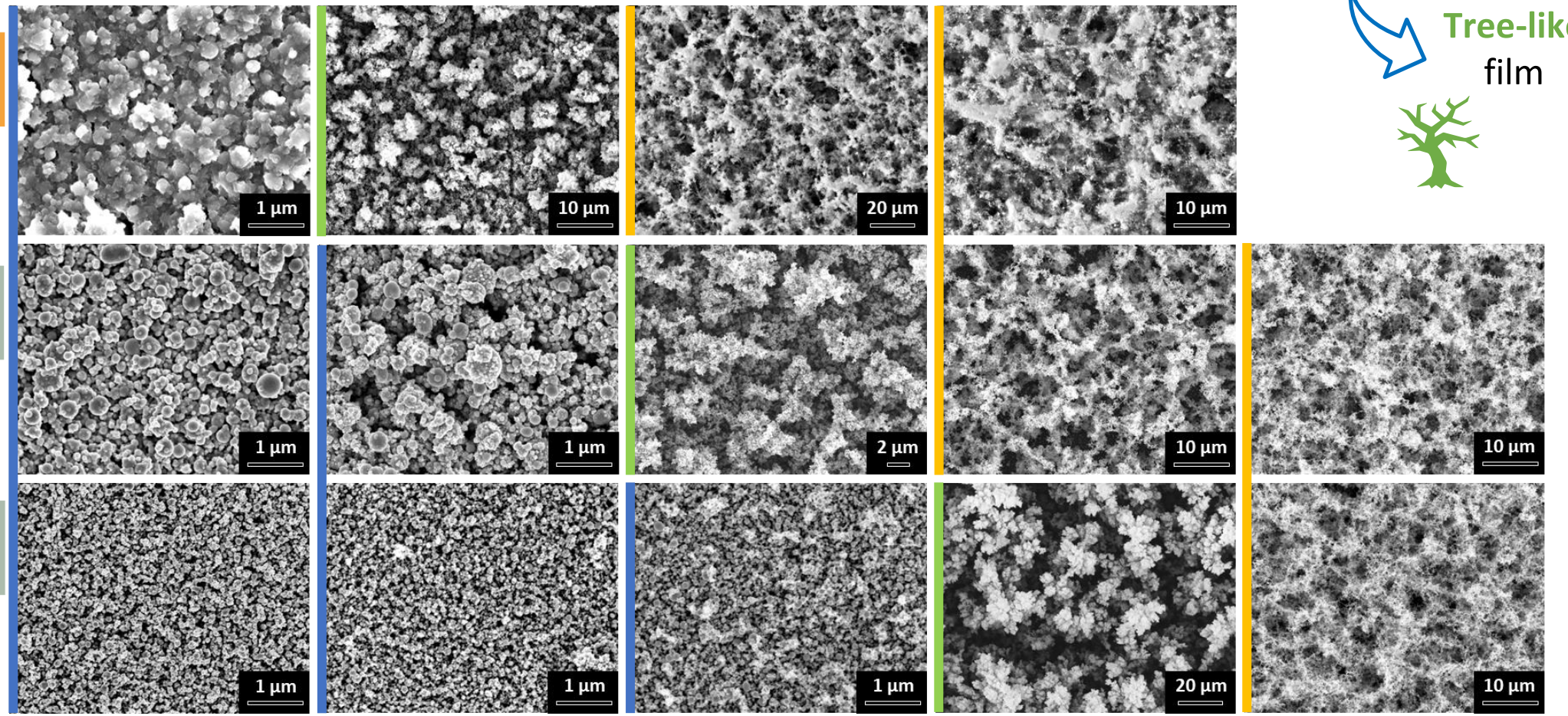
Morphology and gas pressure

Different **magnification**

Nanoparticle-assembled compact film

Tree-like film

Web-like **nanofoam**



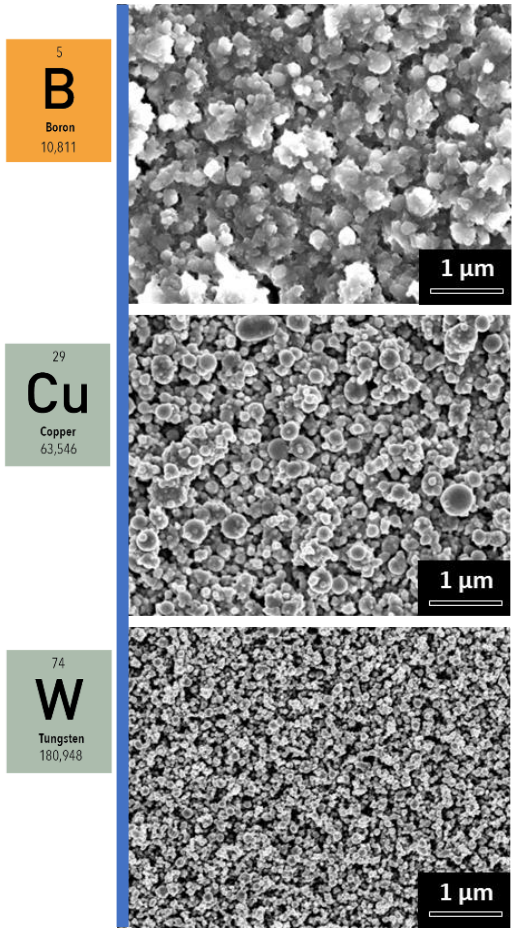
10^{-3} Pa | 100 Pa | 400 Pa | 1000 Pa | 5000 Pa

Argon gas **pressure**

Same morphology evolution

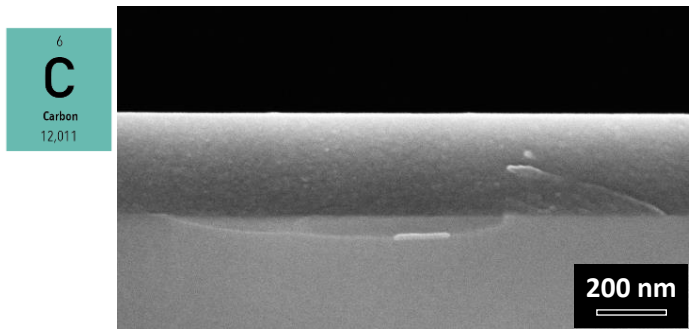
Different pressure thresholds

Morphology and gas pressure



+ 79 Au Gold 196,967 + 14 Si Silicon 28,086

cross section



Compact solid film

!

same as **ns-PLD** ⇨ **No direct** nanoparticles ⇨ Unique **exception**

Nanoparticle-assembled compact film

Tree-like film

Web-like **nanofoam**

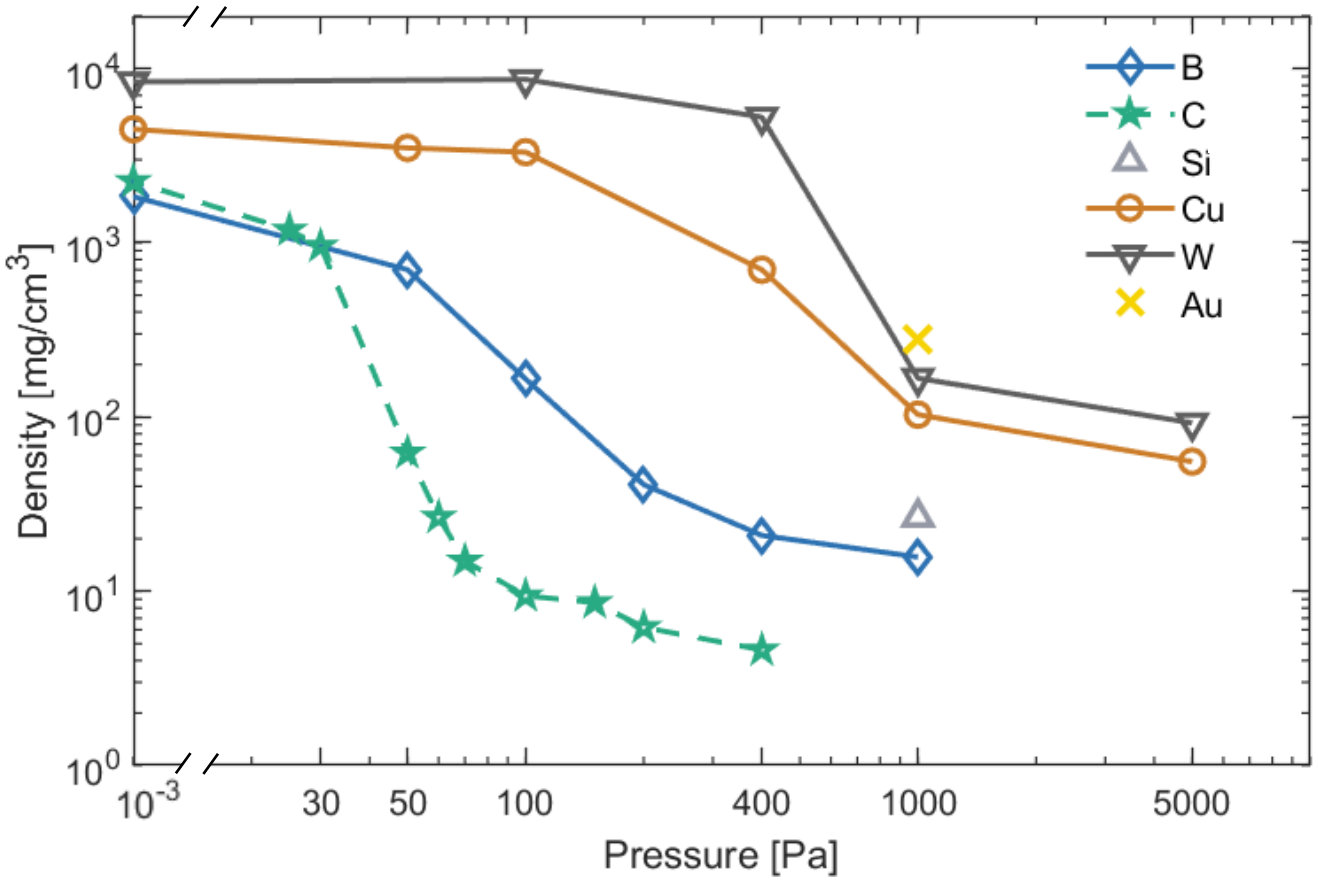
Direct deposition (limited interaction)

Ballistic aggregation

Cluster-cluster aggregation

Average density and gas pressure

Dimensions, **energetics** and **concentration** of the ablated species



Very steep dependence of film average density on deposition pressure

Relative **slowing efficiency** of the background gas

Morphology + **Bulk** density } nanofoam average **density**

Target applications

Laser-matter interaction

Challenging requirements on material properties

Few mg/cm³ density

Nanostructure and **composition** control

Synergy between **ns-PLD** and **fs-PLD**

@ CMD30-FisMat joint conference

MC_49: Italian plasma physics minicolloquium

Invited: *Theoretical investigations of laser-plasma interaction with low-density nanostructured targets at PoliMi*

M. Galbiati

Poster: *Target production for particle acceleration from laser interaction with near-critical nanostructured plasma*

F. Mirani

Oral: *Carbon nanofoam targets for inertial confinement fusion experiments*

A. Maffini

Target applications

Laser-matter interaction

Challenging requirements on material properties

Few mg/cm³ density

Nanostructure and **composition** control

Synergy between **ns-PLD** and **fs-PLD**

Laser-driven **proton-boron fusion**

$$p + {}^{11}B \rightarrow 3\alpha + 8.7\ MeV$$

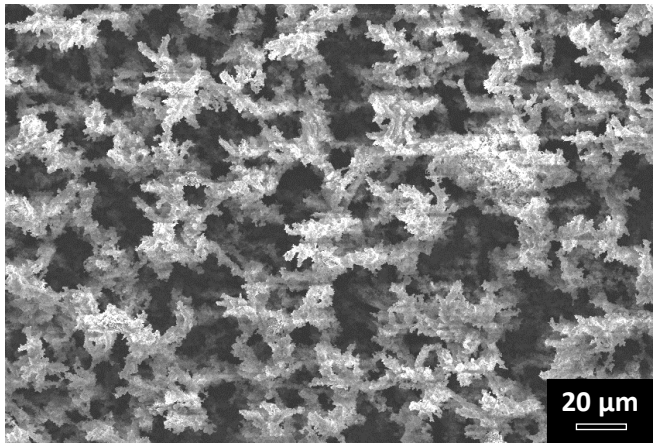
Hydrogen enriched boron foam

Codeposition of boron and H-rich polymers

Thanks to the **fs-PLD universality**

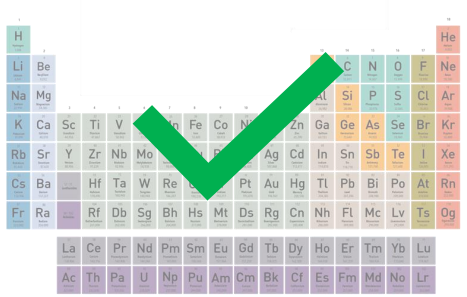
Boron PLD target

HDPE inset



- H/B ratio of $\sim 1-2$
- $\sim 100\ \mu m$ thickness
- $\sim 50-100\ mg/cm^3$ density
- 20% C, 10% O, 1% Mg

Conclusions and perspectives



fs-PLD is a **universal technique** for low-density **nanofoam** production

- **Versatile**
- **Flexible**

ns-PLD and **fs-PLD** as **complementary** techniques

Dimensions, **energetics** and **concentration** of the ablated species

Relative **slowing efficiency** of the background gas

Nanofoam properties

Enlarge the study to **other elements** and **compounds**

Model the **ablation, aggregation** and **growth** quantitatively

Test, optimize and employ the nanofoam materials in **relevant applications**

Thank you for your attention!

davide.orecchia@polimi.it