



4th International Workshop on Proton-Boron Fusion

30th September – 3rd October 2024

FRASCATI, ITALY

Synthesis, characterization and testing of hydrogenated boron nanofoams for laser-driven proton-boron fusion

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G. Nersisyan², V. Kantarelou⁴, L. Giuffrida⁴, D. Margarone^{2,4}



POLITECNICO
MILANO 1863



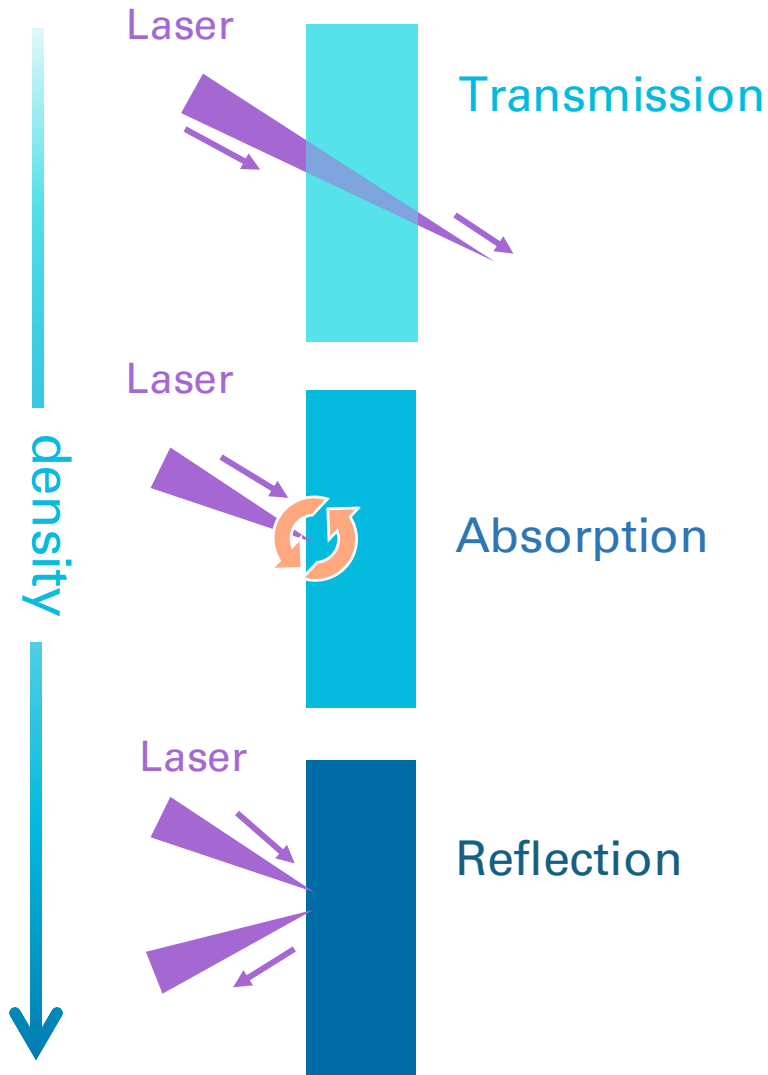
QUEEN'S
UNIVERSITY
BELFAST



Synthesis, characterization and testing of hydrogenated boron nanofoams for laser-driven proton-boron fusion

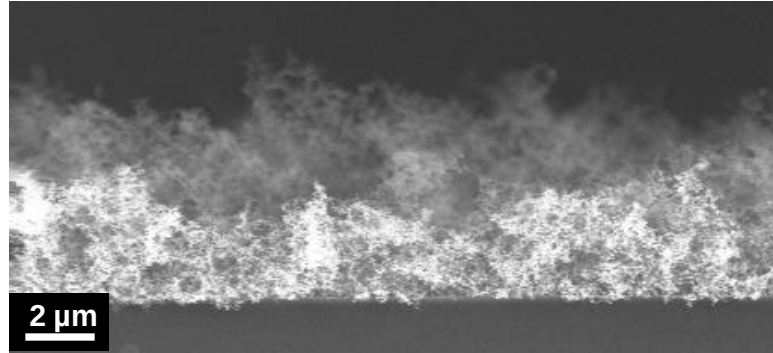
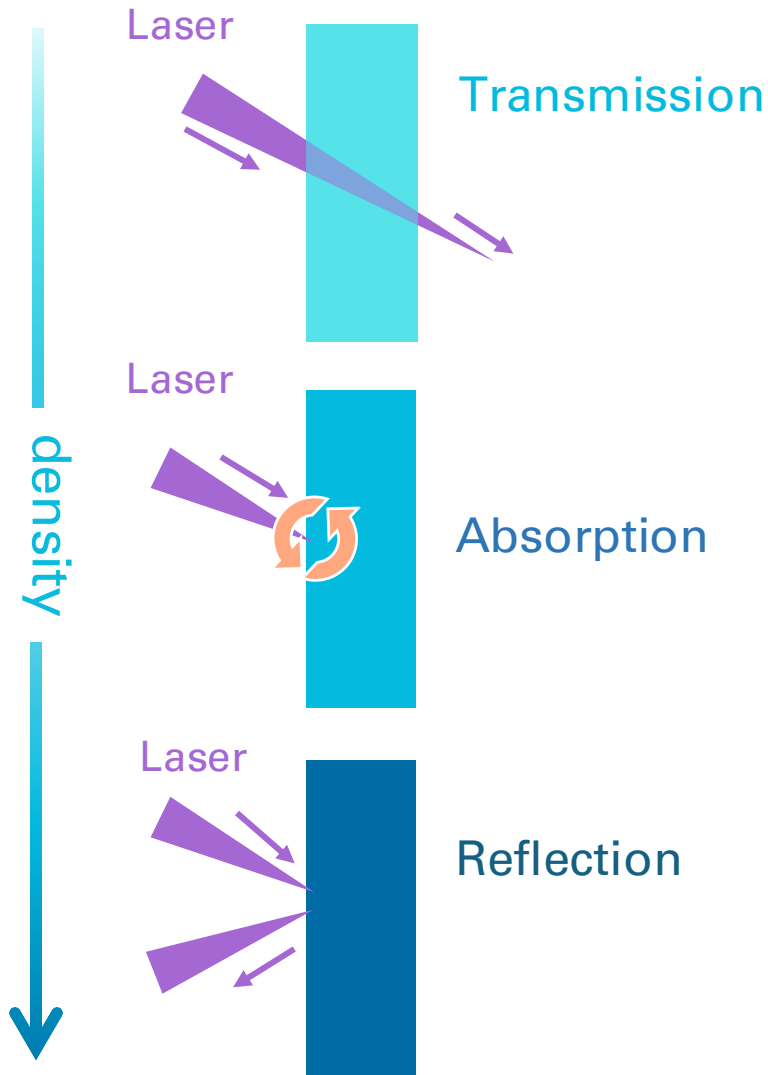
Synthesis, characterization and testing of hydrogenated boron **nanofoms for laser-driven** proton-boron fusion

Why Nanofoams?



$$n_c = \frac{m_e \omega_L^2}{4\pi e^2} \approx$$

Why Nanofoams?

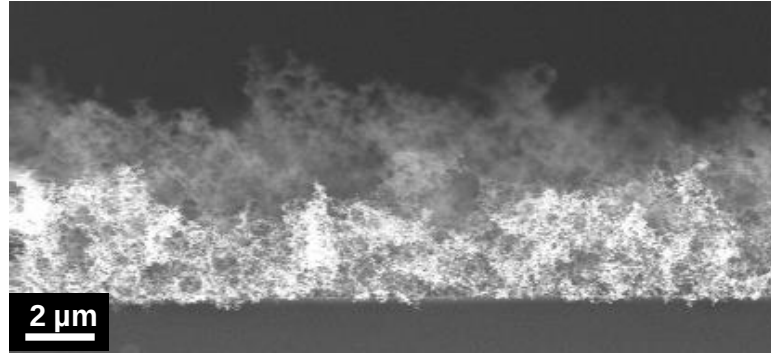
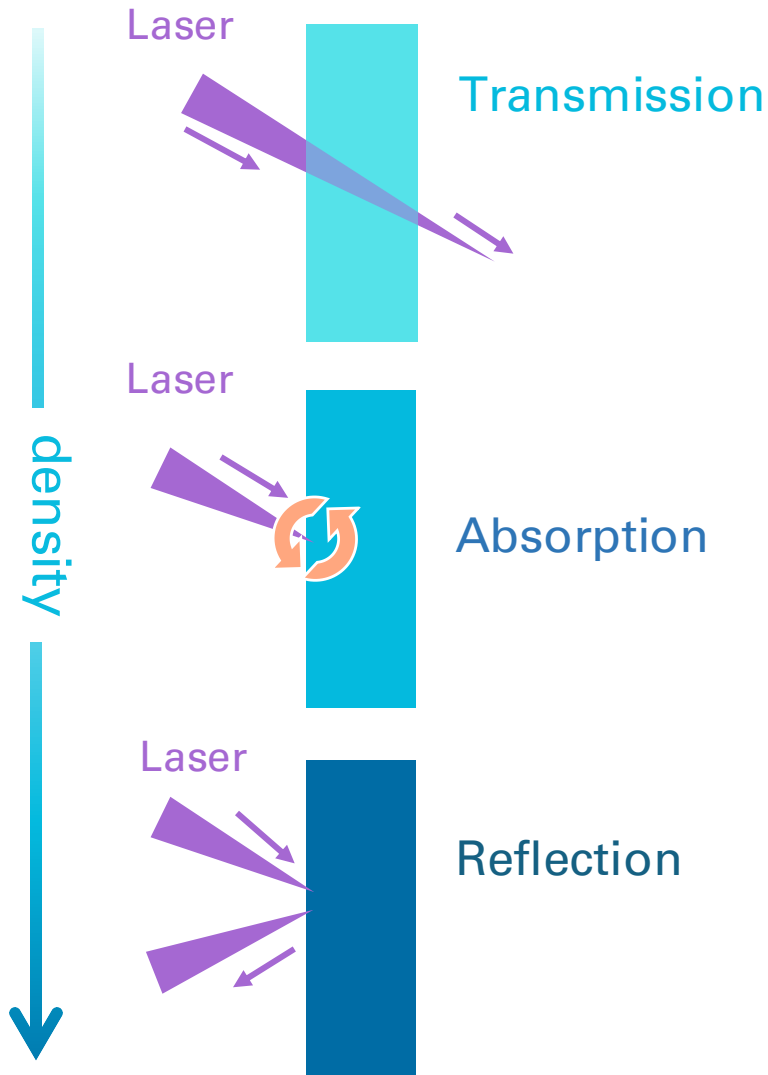


Nanostructured materials

$$n_c = \frac{m_e \omega_L^2}{4\pi e^2} \approx \text{few } \frac{mg}{cm^3}$$

Volumetric interaction

Why Nanofoams?



Nanostructured materials

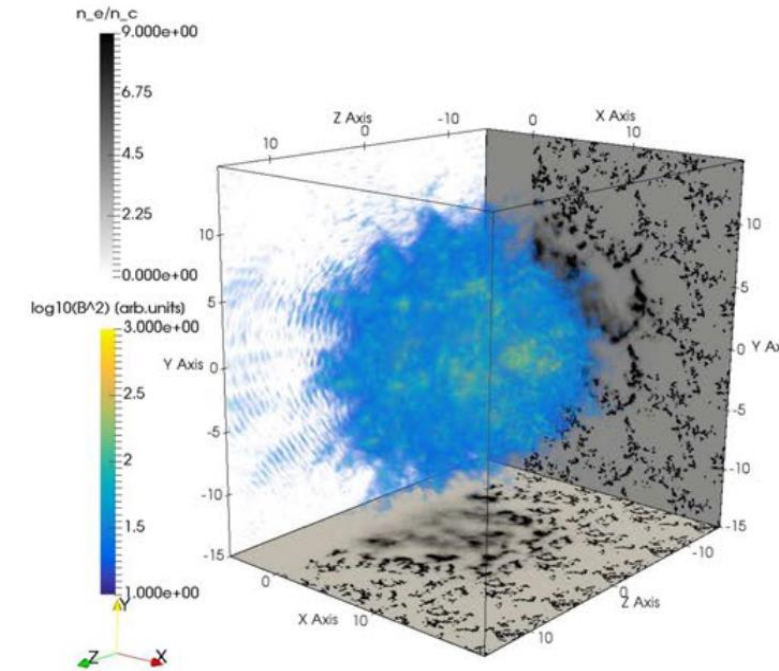
$$n_c = \frac{m_e \omega_L^2}{4\pi e^2} \approx \text{few } \frac{mg}{cm^3}$$

Volumetric
interaction

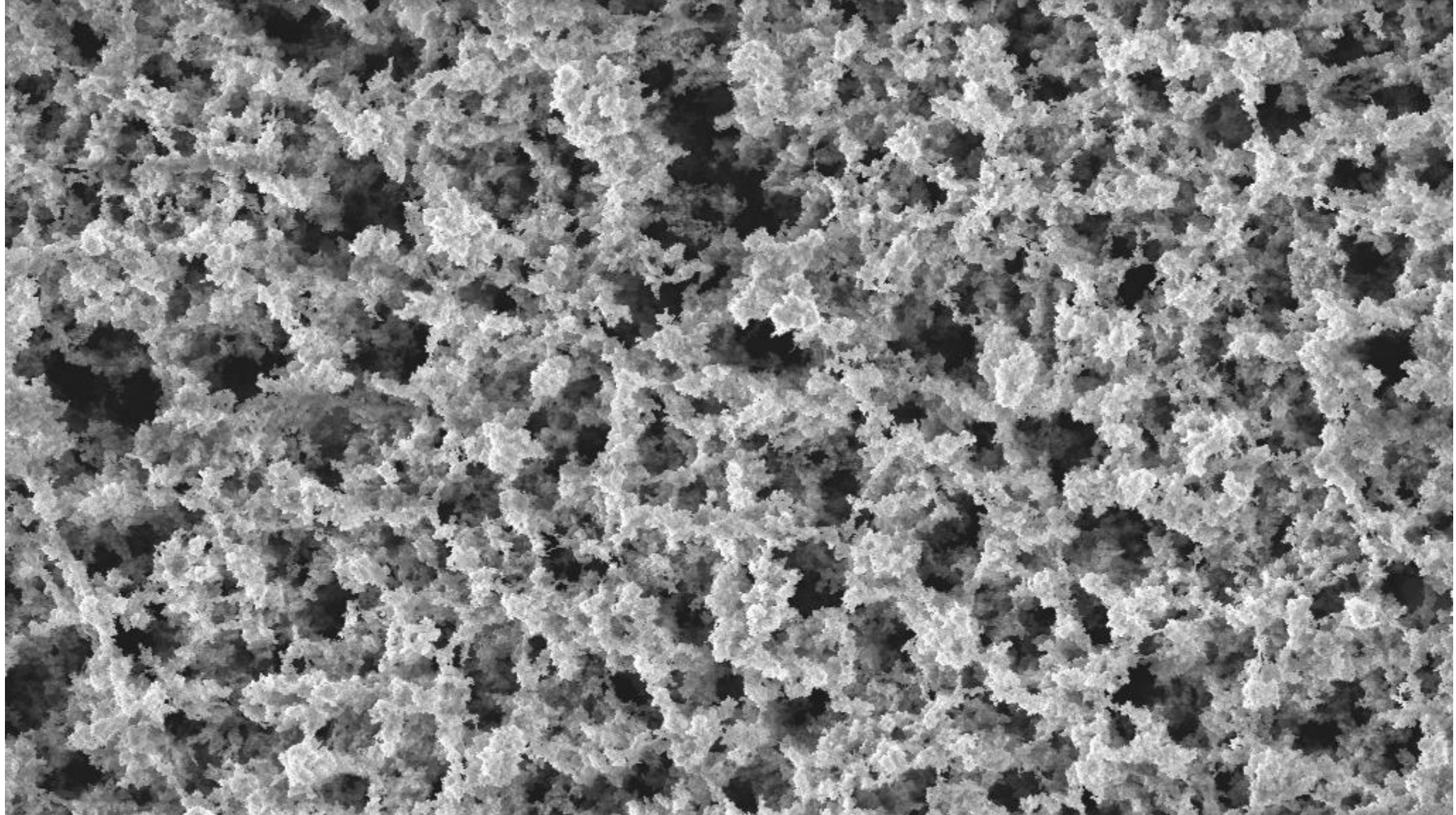
Nanostructure
enhancement



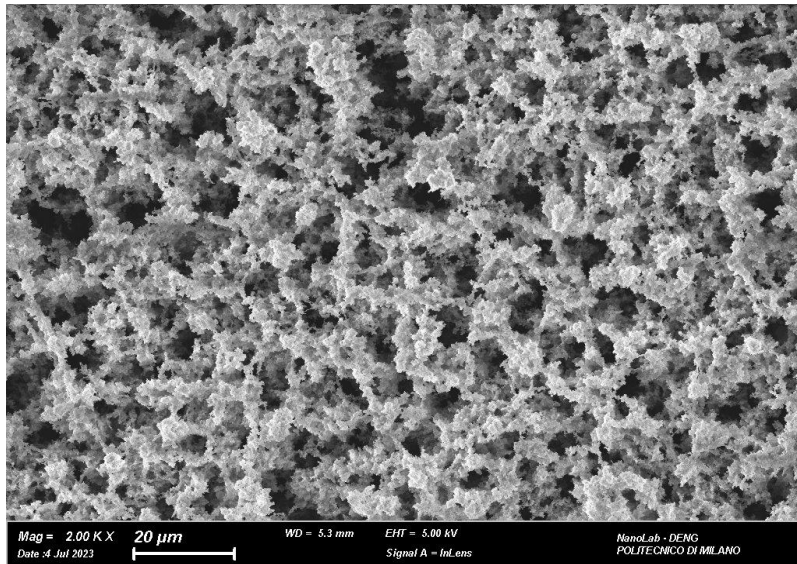
Efficient
laser absorption



Why Pulsed Laser Deposited (PLD) Nanofoams?



How PLD nanofoams look like

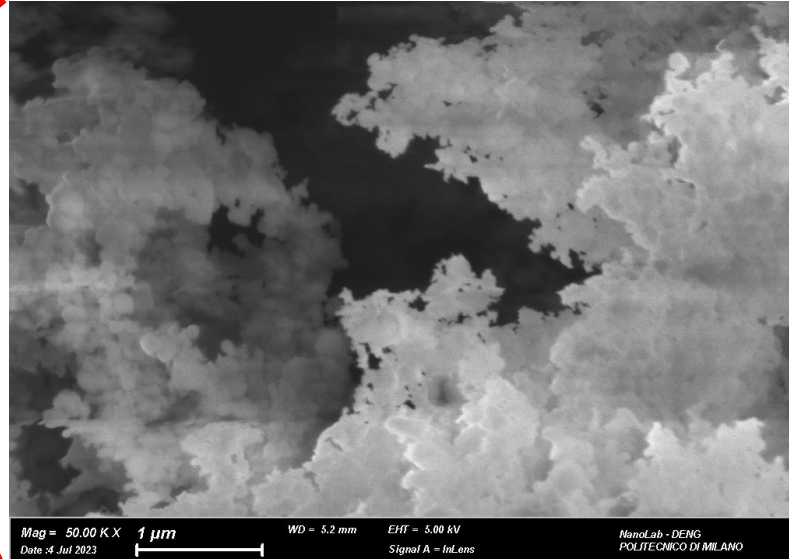
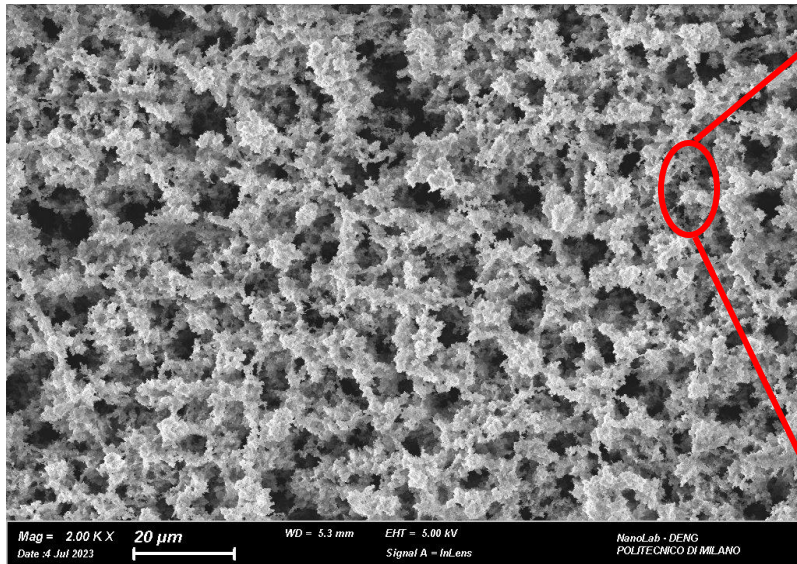


Multi-scale structure

Thickness: 1 to 100s μm

Area: from 1 mm^2 to 10 cm^2

How PLD nanofoams look like

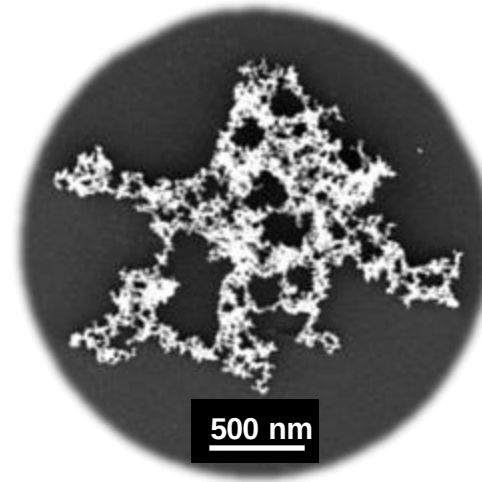


Multi-scale structure

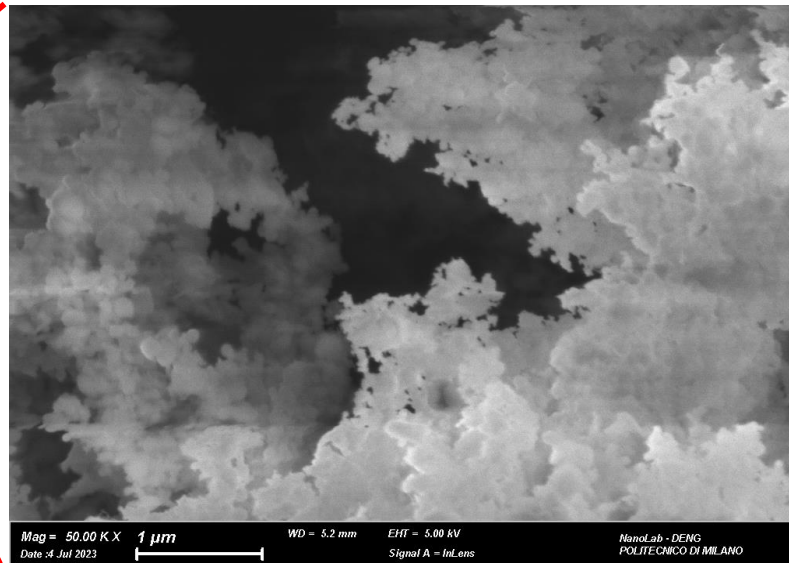
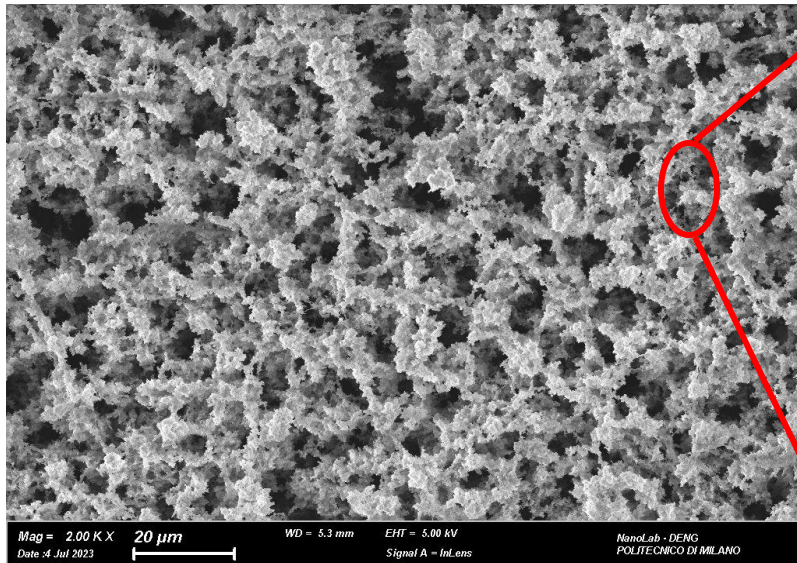
Thickness: 1 to 100s μm

Area: from 1 mm² to 10 cm²

Fractal-like aggregates



How PLD nanofoams look like

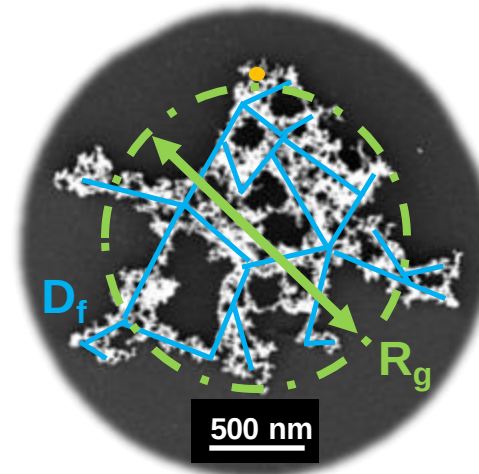


Multi-scale structure

Thickness: 1 to 100s μm

Area: from 1 mm² to 10 cm²

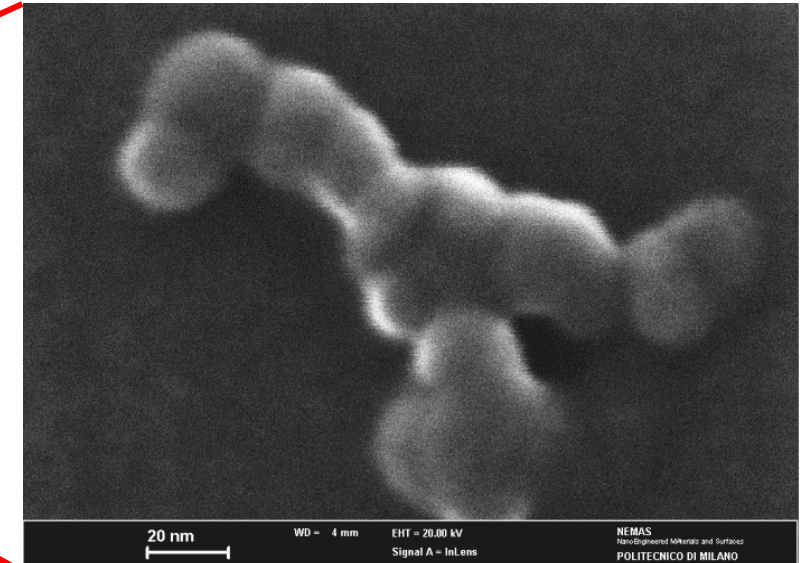
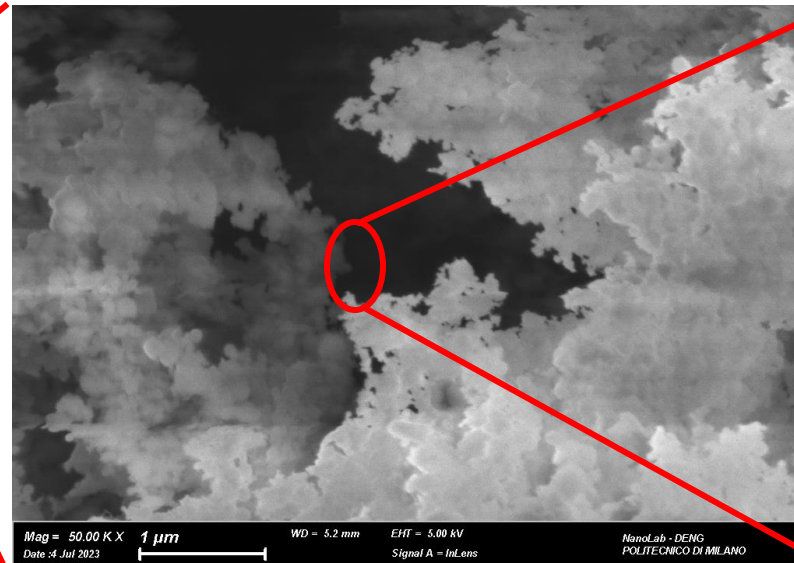
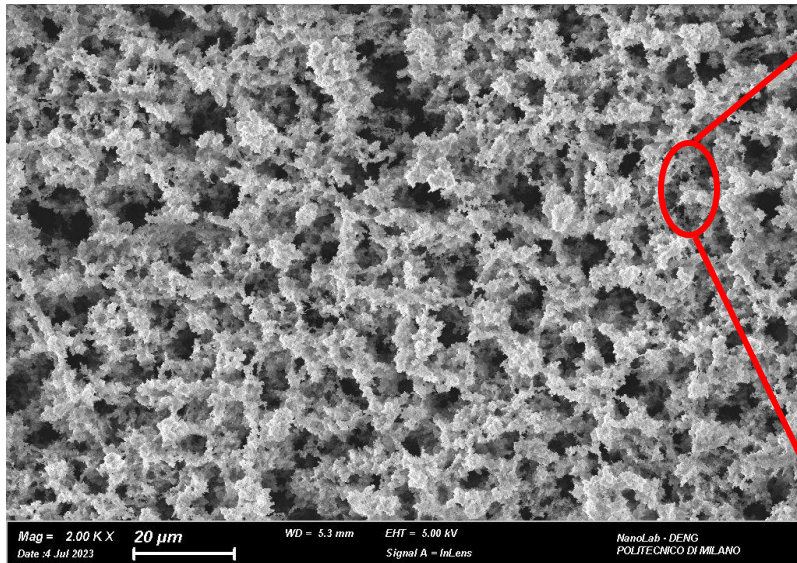
Fractal-like aggregates



D_f Fractal dimension: $\sim 1.8 - 2.2$

R_g Gyration radius: $0.1 \mu\text{m} - 5 \mu\text{m}$

How PLD nanofoams look like

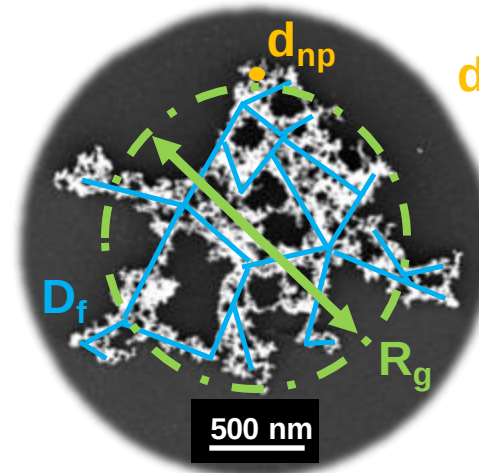


Multi-scale structure

Thickness: 1 to 100s μm

Area: from 1 mm^2 to 10 cm^2

Fractal-like aggregates

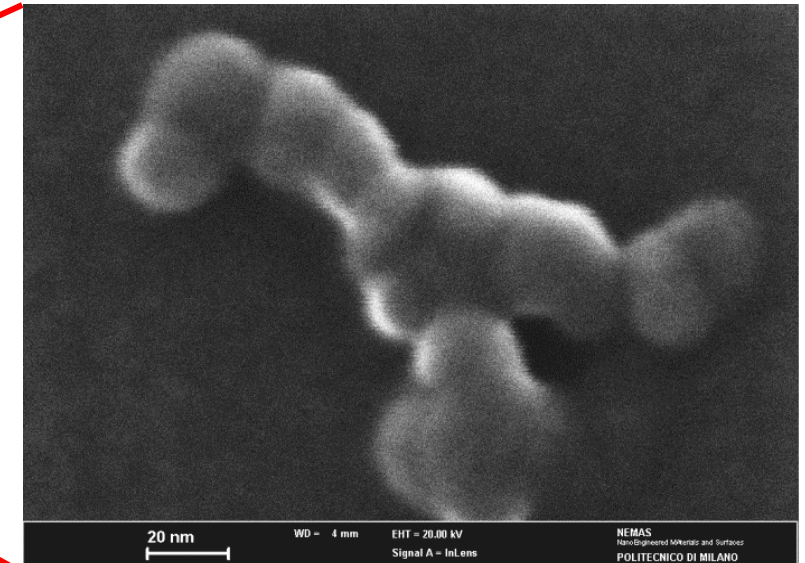
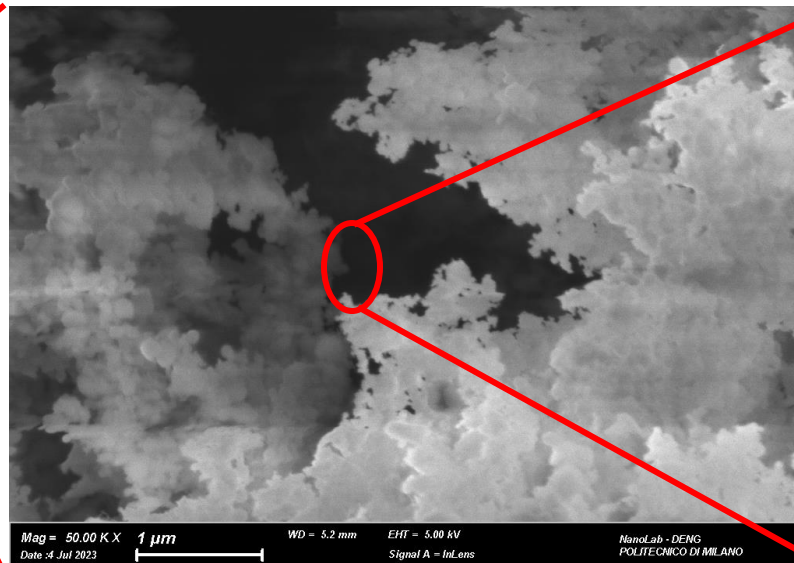
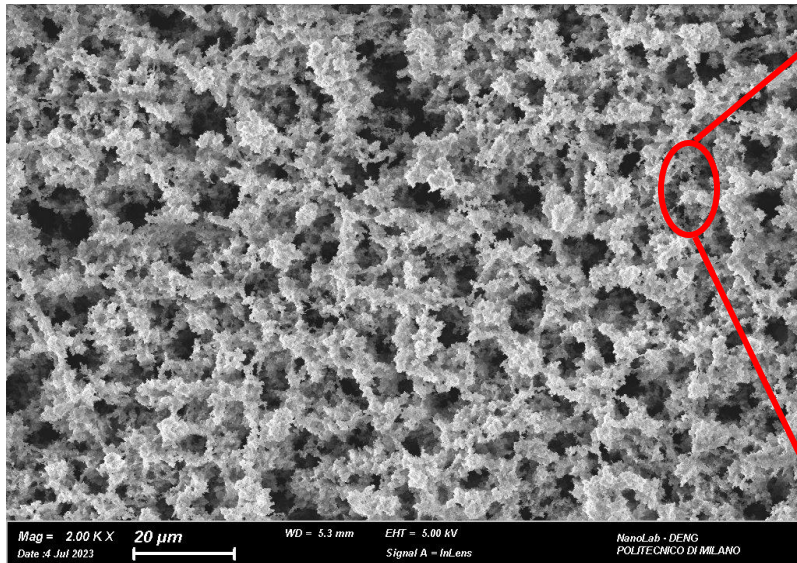


d_{np} Nanoparticle diameter: 5 nm – 40 nm
Nanoparticle density: $\sim 50\% - 100\%$ of bulk
Nanoparticle composition: any!

D_f Fractal dimension: $\sim 1.8 - 2.2$

R_g Gyration radius: 0.1 μm – 5 μm

How PLD nanofoams look like



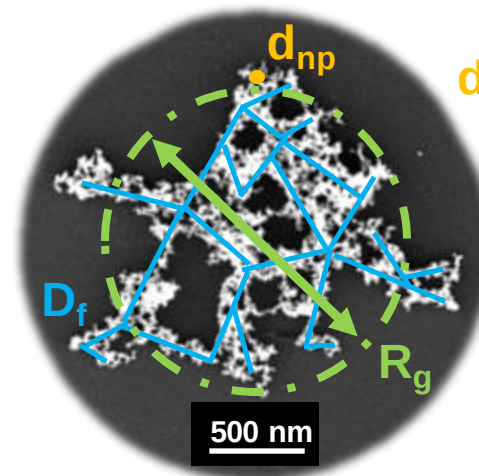
Multi-scale structure

Thickness: 1 to 100s μm

Area: from 1 mm^2 to 10 cm^2

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

Fractal-like aggregates



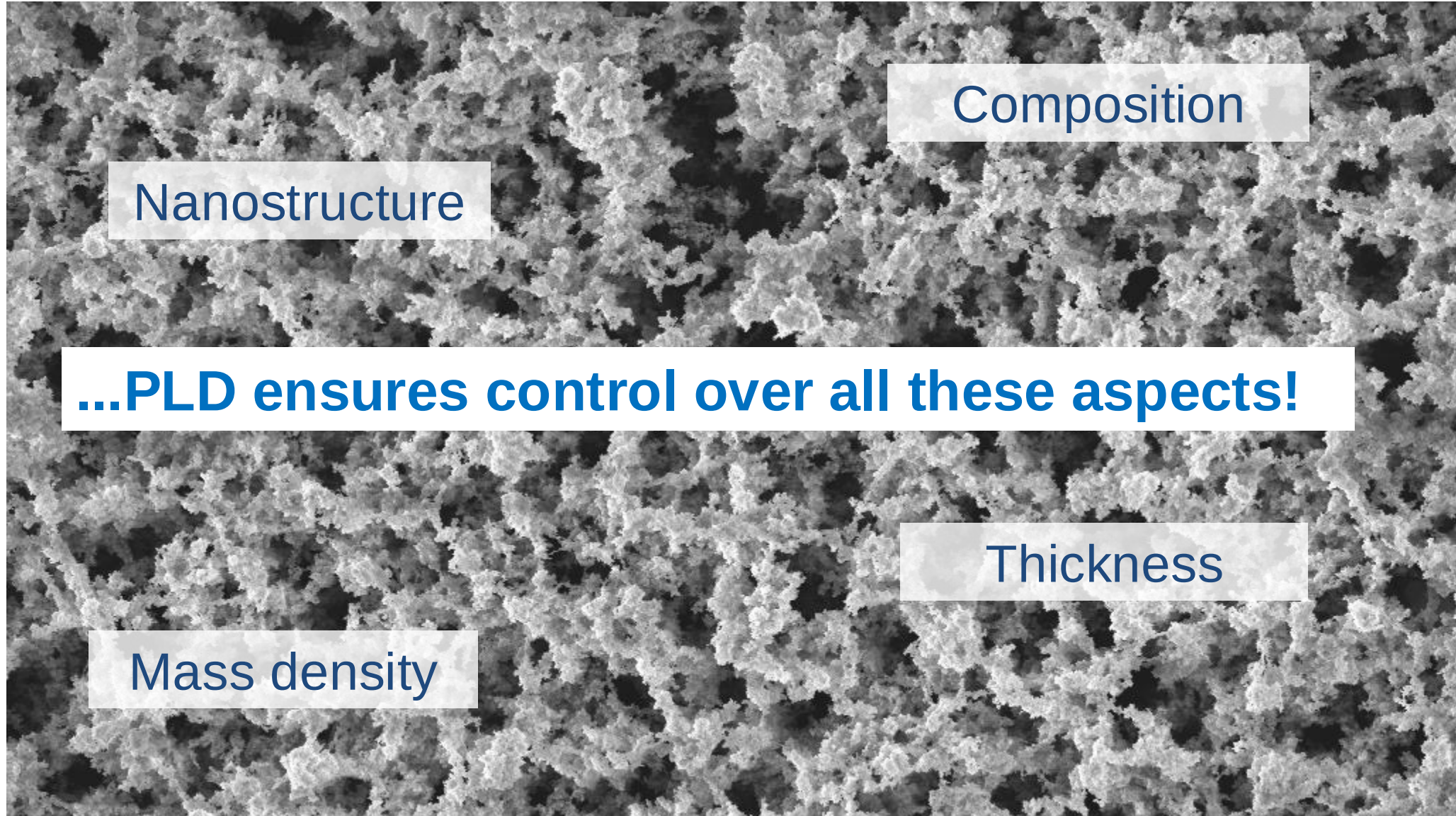
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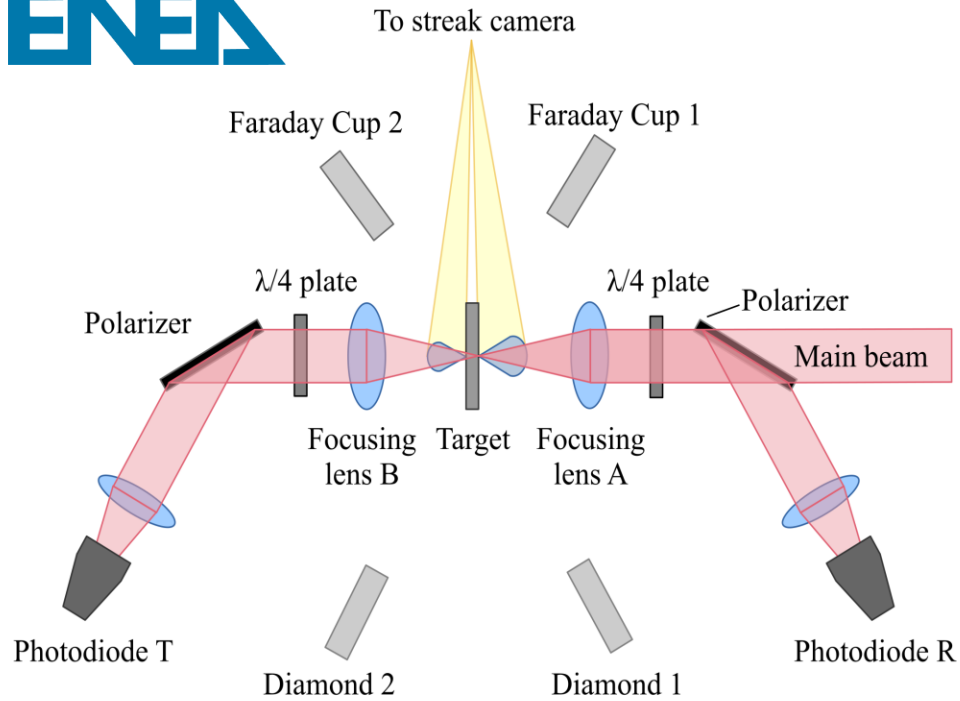
Nanoparticle constituents

Why Pulsed Laser Deposited Nanofoams?



Synthesis, characterization and **testing** of hydrogenated boron **nanofoms** for **laser**-driven proton-boron fusion

Nanofoams as ICF ablators



Wavelength = 1054 nm
Temporal FWHM = 3 ns
Intensity = 10^{14} W/cm²
 $E_p = 40$ J

See [M. Cipriani](#)'s talk this morning!

No foam



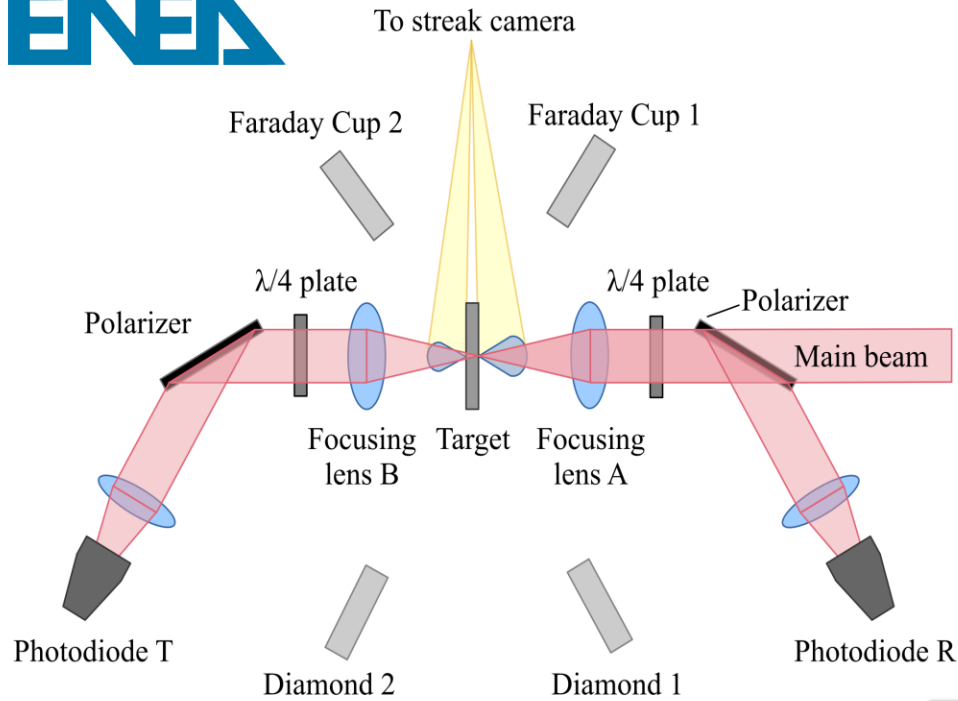
Fractal-like



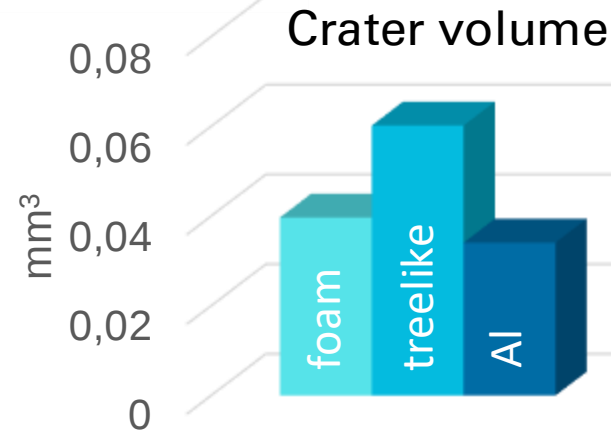
Tree-like



Nanofoams as ICF ablaters

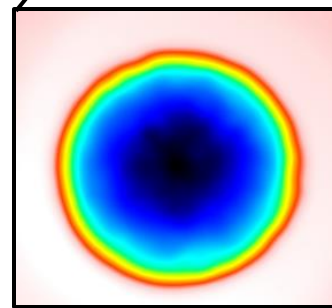
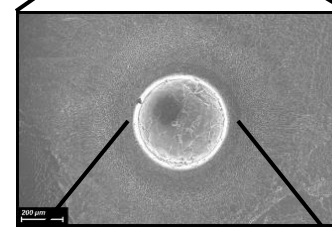
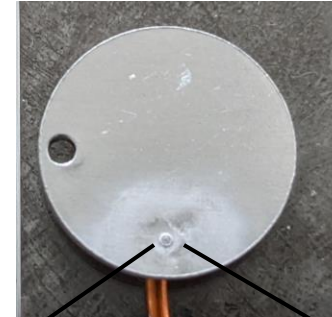


Wavelength = 1054 nm
 Temporal FWHM = 3 ns
 Intensity = 10^{14} W/cm²
 Ep = 40 J



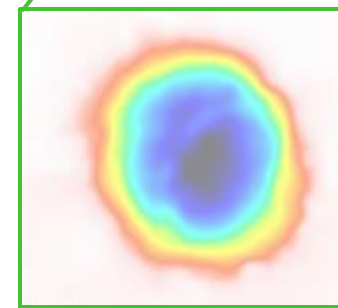
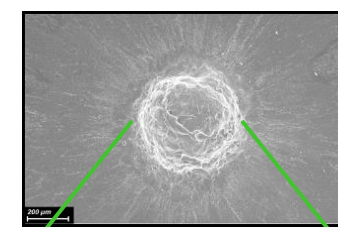
See [M. Cipriani's](#) talk this morning!

No foam



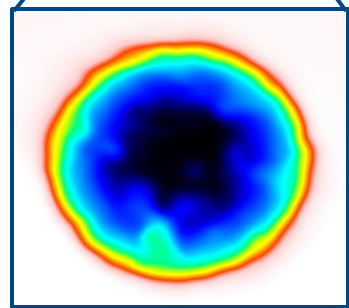
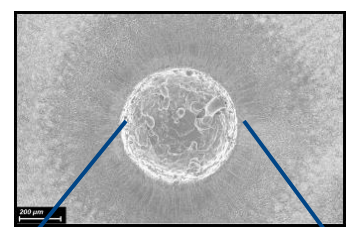
$$V \sim 3 \cdot 10^7 \mu\text{m}^3$$

Fractal-like



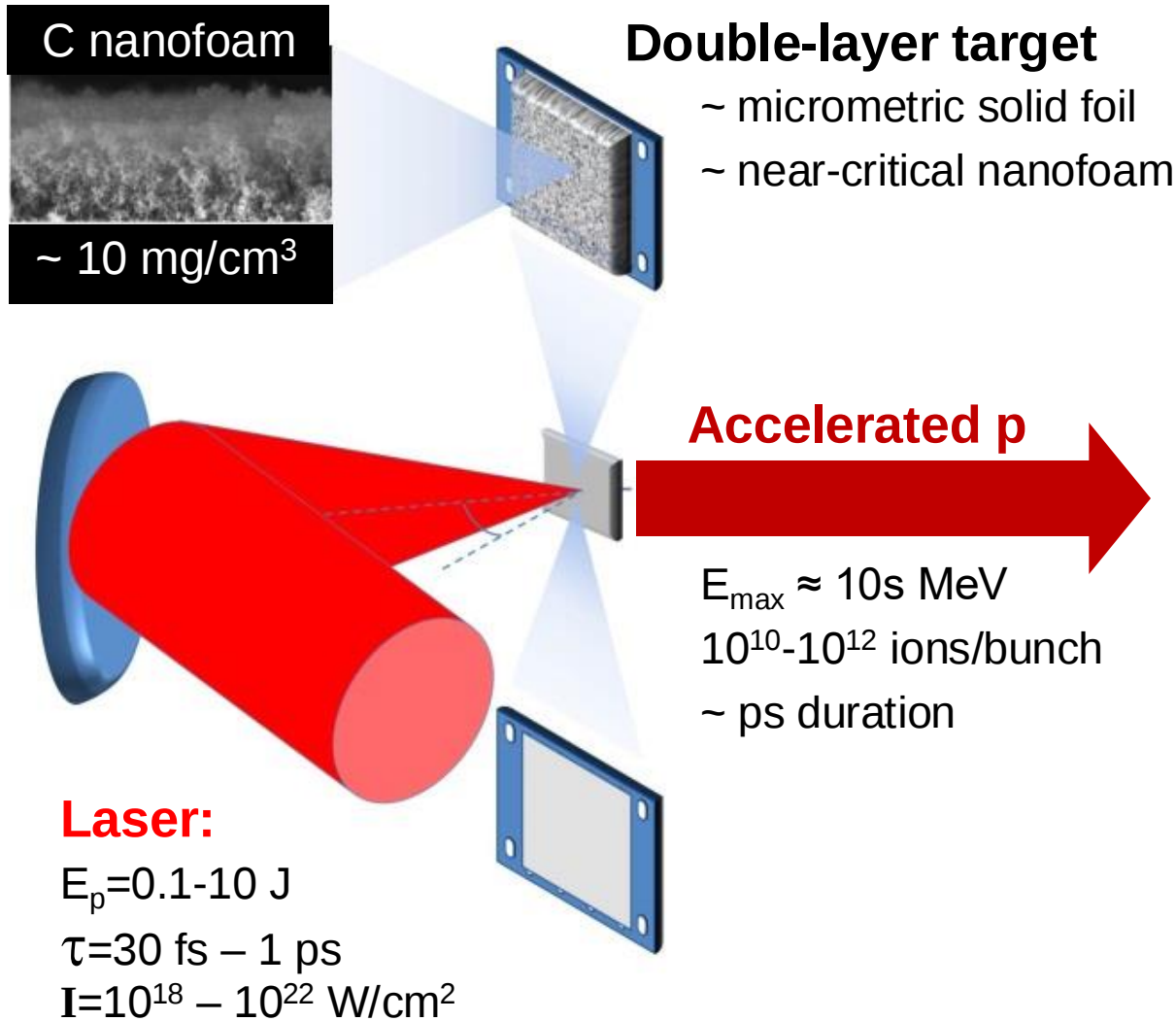
$$V \sim 4 \cdot 10^7 \mu\text{m}^3$$

Tree-like

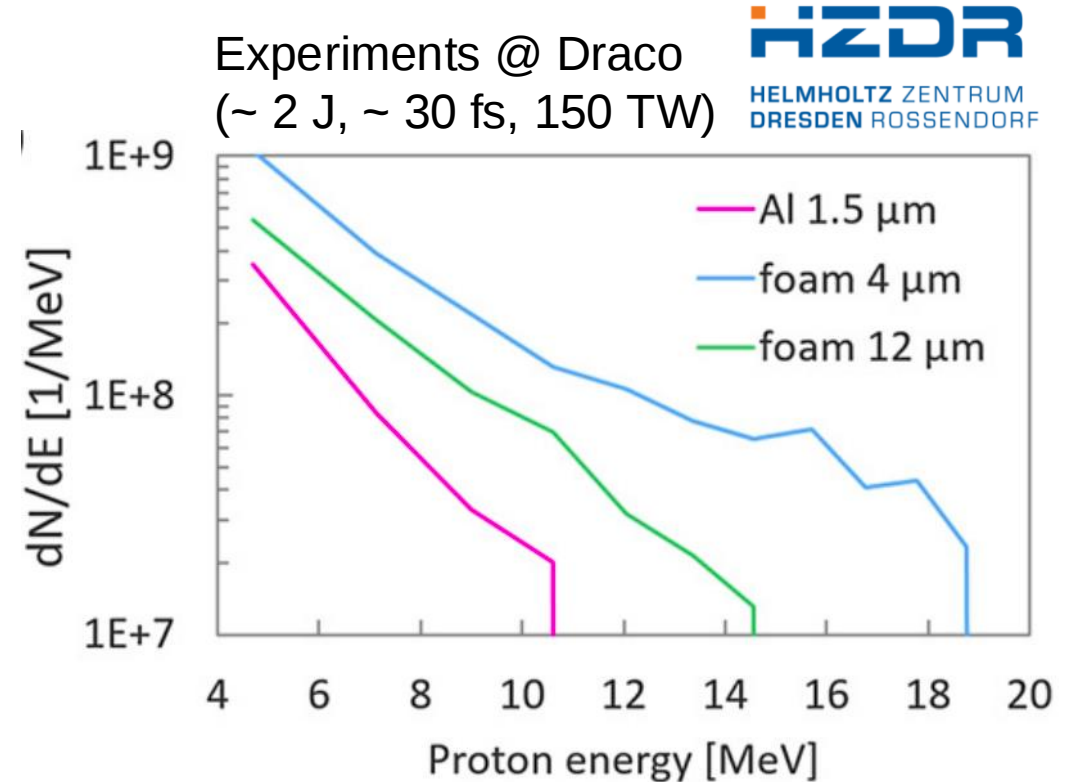
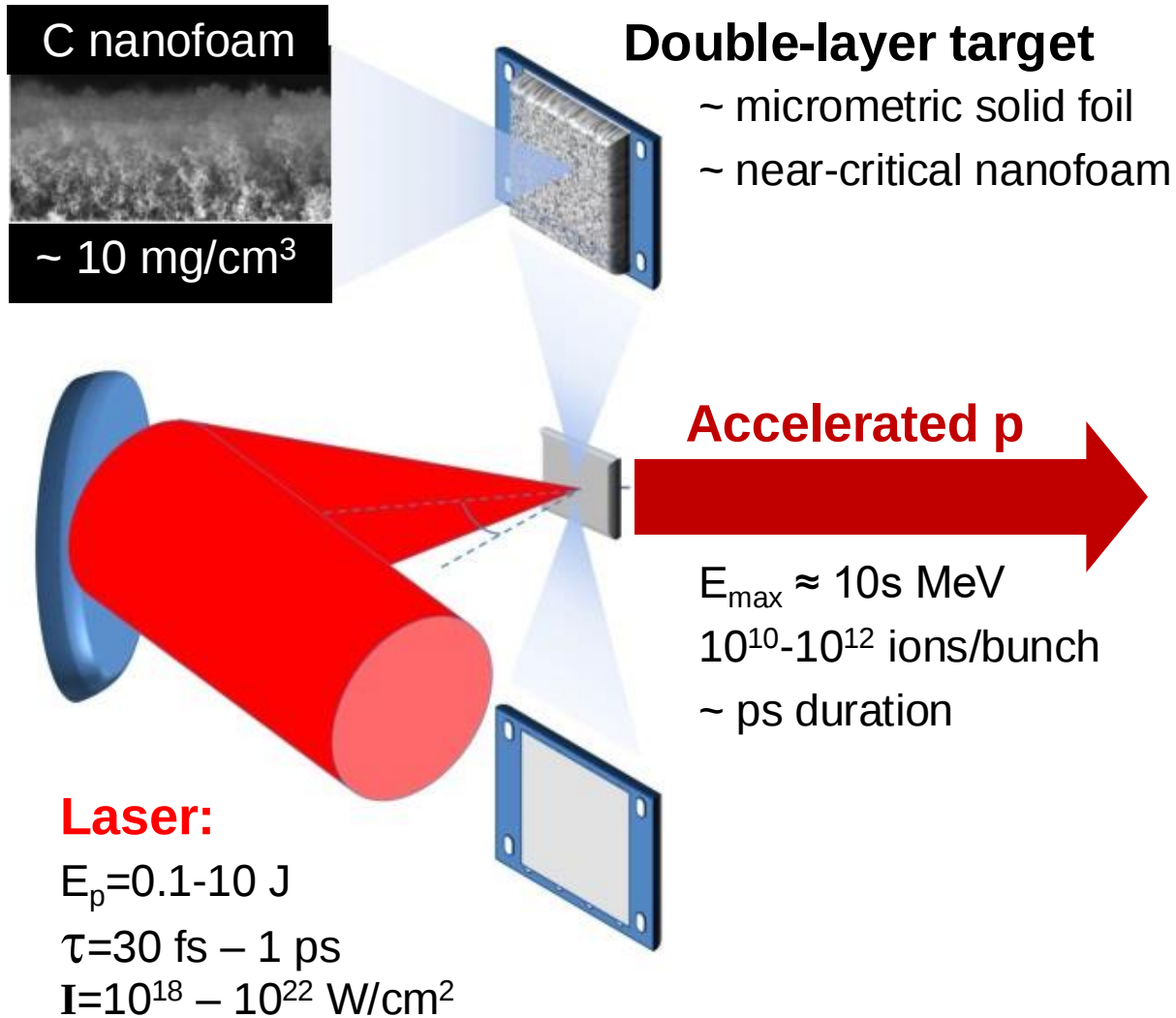


$$V \sim 6 \cdot 10^7 \mu\text{m}^3$$

Nanofoams for advanced TNSA

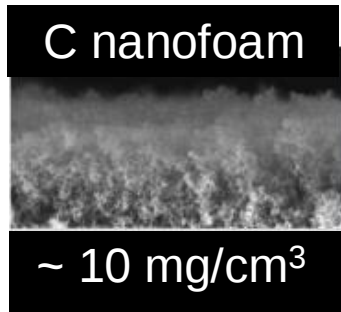


Nanofoams for advanced TNSA



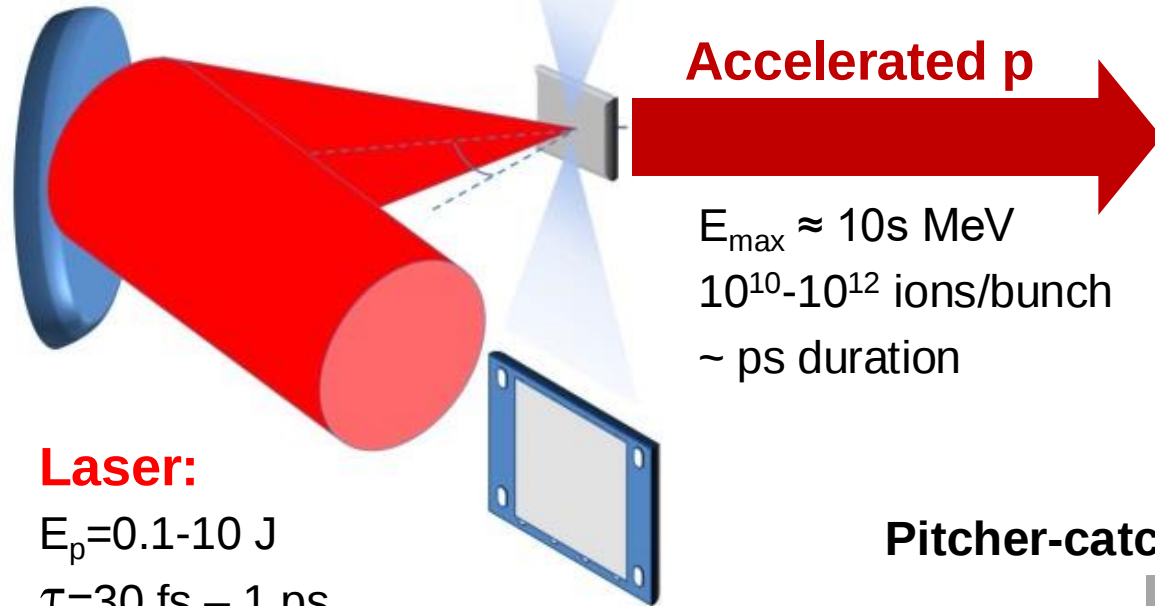
~ x **2** in maximum **energy**!
~ x **4** in **number** of protons!

Nanofoams for advanced TNSA



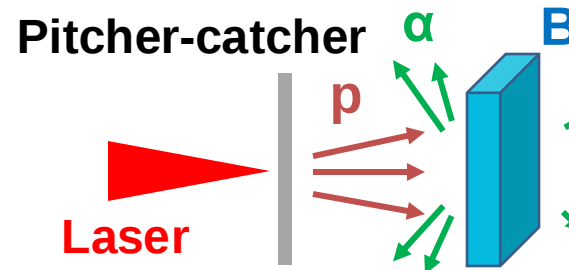
Double-layer target

- ~ micrometric solid foil
- ~ near-critical nanofoam



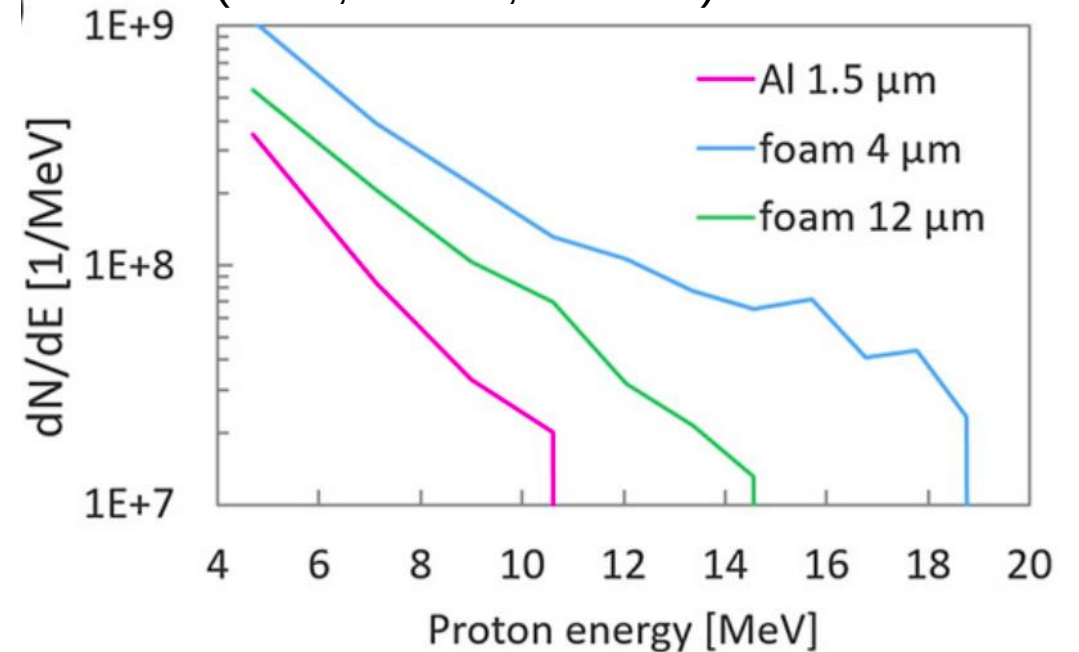
Laser:

$E_p = 0.1\text{-}10\text{ J}$
 $\tau = 30\text{ fs} - 1\text{ ps}$
 $I = 10^{18} - 10^{22}\text{ W/cm}^2$



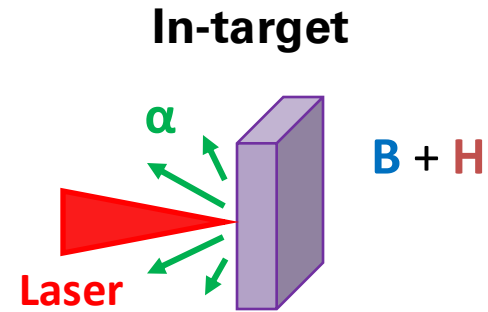
Experiments @ Draco
(~ 2 J, ~ 30 fs, 150 TW)

HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF



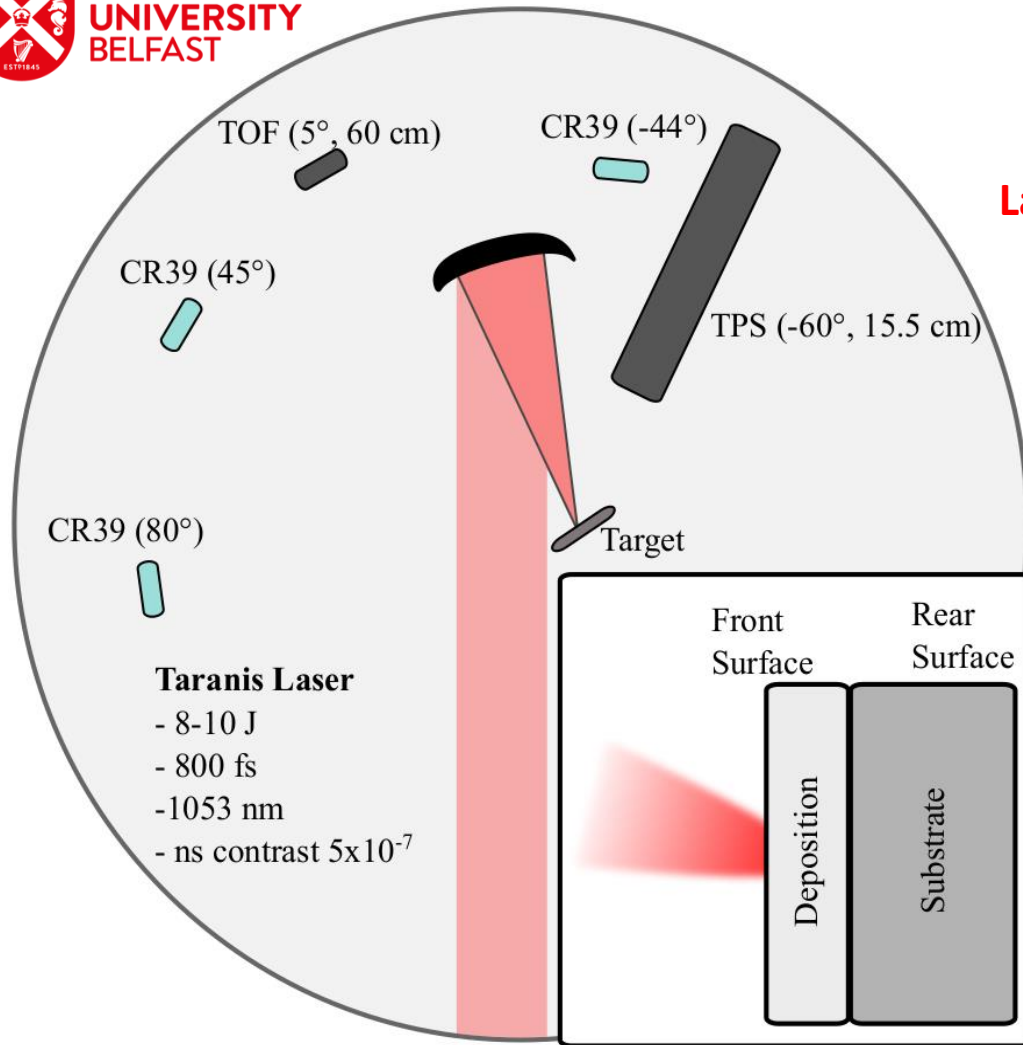
~ x **2** in maximum **energy!**
~ x **4** in **number** of protons!

Nanofoams for in-target p-11B fusion

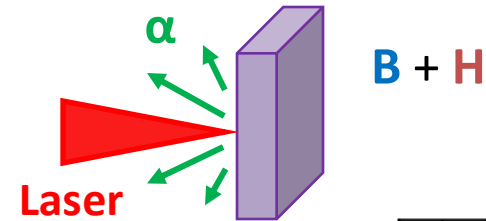


See [D. Molloy](#)'s talk this morning!

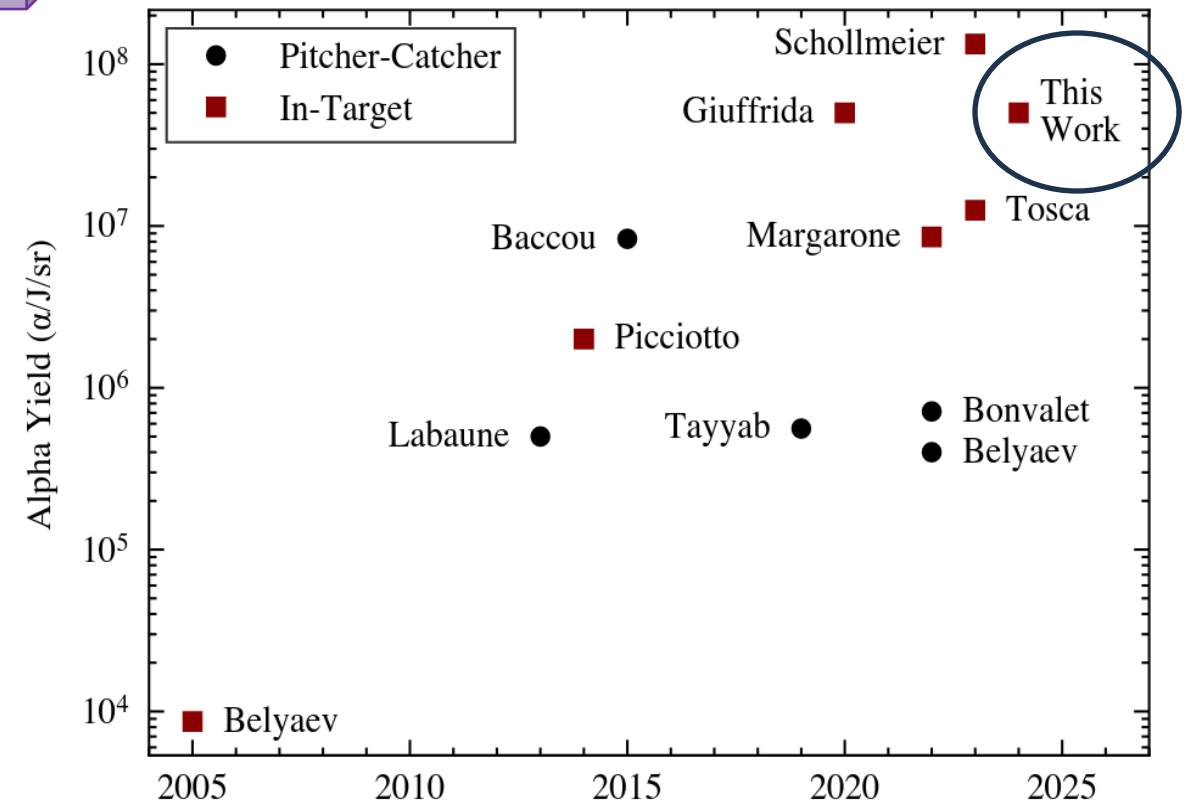
Nanofoams for in-target p-11B fusion



In-target

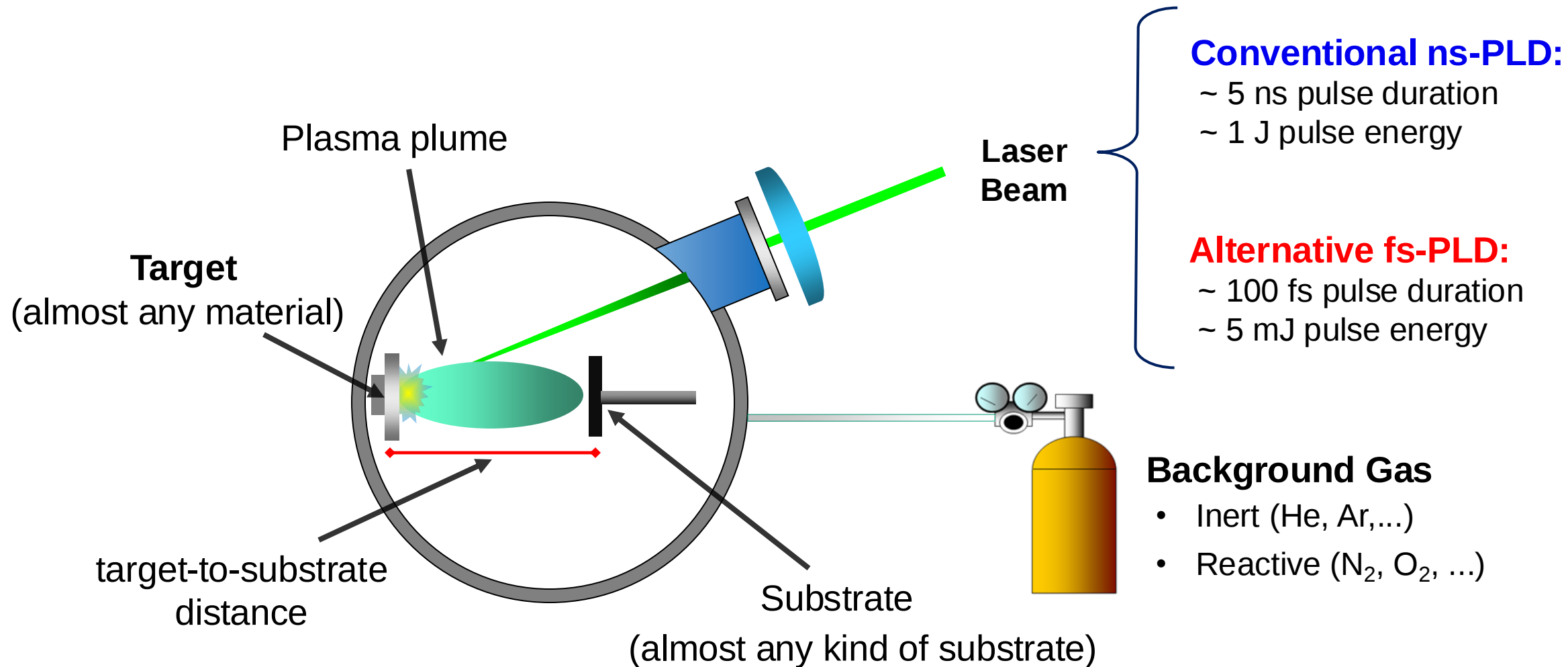


See **D. Molloy's** talk this morning!



Synthesis, characterization and testing of hydrogenated boron nanofoams for laser-driven proton-boron fusion

How does Pulsed Laser Deposition work?



Foam properties control

Nano-scale

- Crystalline structure & composition
- Nanoparticle size

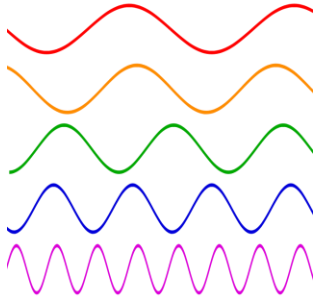
Micro-scale

- Aggregate size
- Morphology

Macro-scale

- Uniformity
- Thickness profile

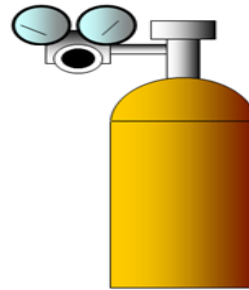
Pulse Duration



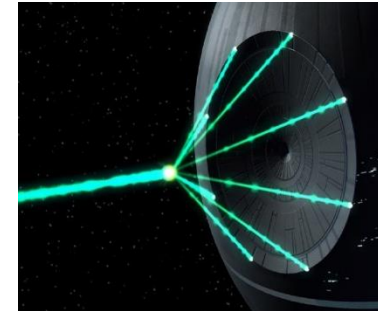
Target composition



Gas pressure



Laser Fluence

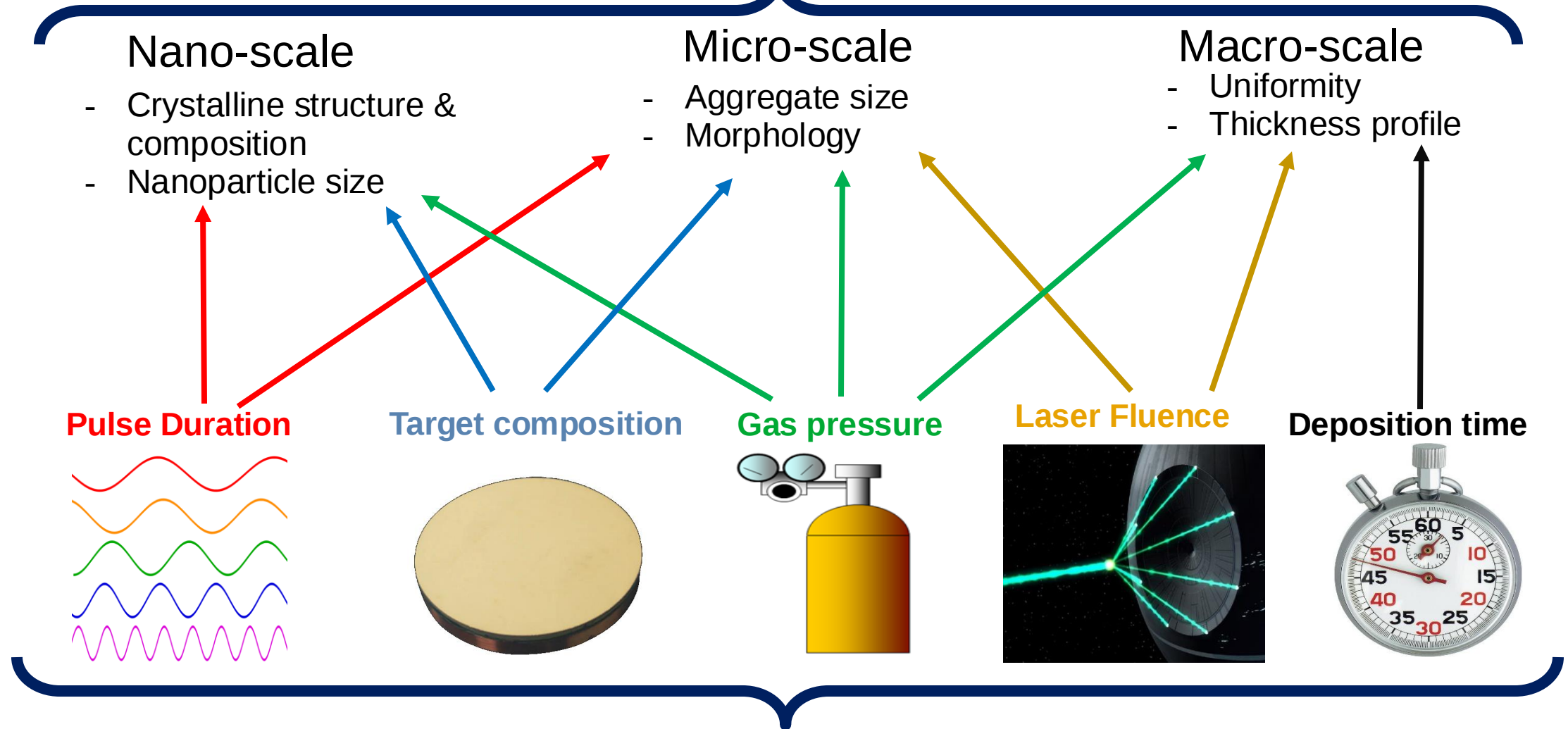


Deposition time



PLD process parameters

Foam properties control



PLD process parameters

Foam properties control

Nano-scale

- Crystalline structure & composition
- Nanoparticle size

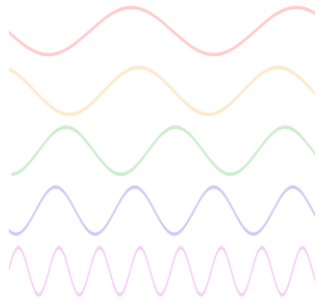
Micro-scale

- Aggregate size
- Morphology

Macro-scale

- Uniformity
- Thickness profile

Pulse Duration



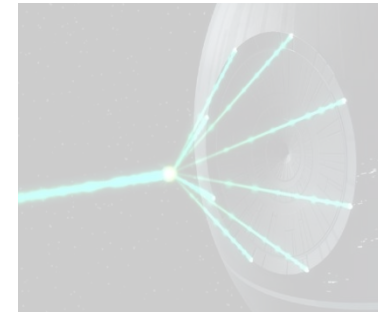
Target composition



Gas pressure



Laser Fluence



Deposition time



PLD process parameters

A lot of elements to play with...

The image displays a periodic table of elements, color-coded by groups. The elements are arranged in their standard periodic table layout. Each element's cell contains its symbol, name, and atomic number. The background color of each cell indicates the element's group: Group 1 (pink), Group 2 (light blue), Groups 3-10 (light green), Groups 11-18 (light orange), and Groups 19-20 (light pink). The lanthanide and actinide series are shown at the bottom in a separate row, colored light purple.

A lot of elements to play with...

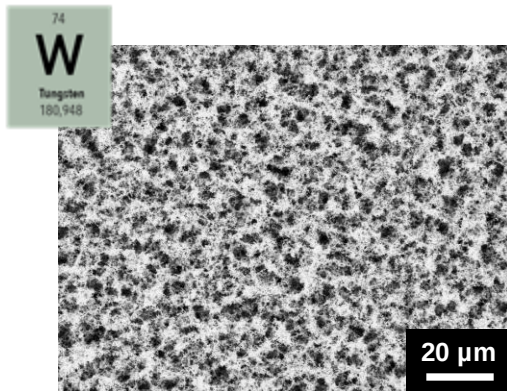
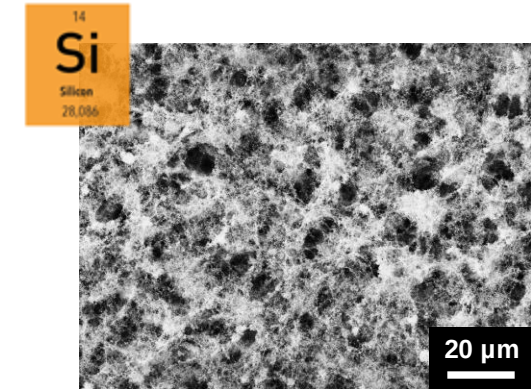
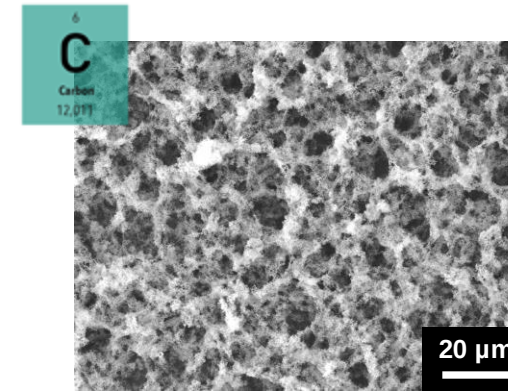
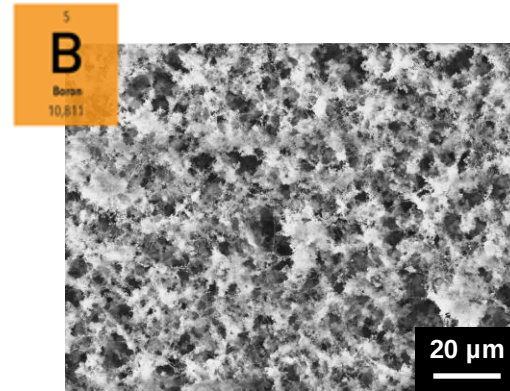
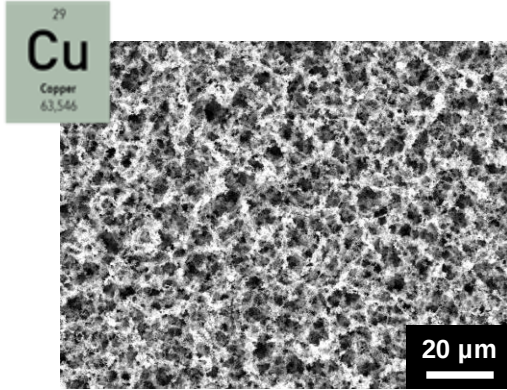
The image shows a periodic table of elements. Several elements are highlighted in colored boxes, each containing the element's symbol, name, and atomic number:

- Hydrogen (H)**: Atomic number 1, highlighted in a light blue box.
- Boron (B)**: Atomic number 5, highlighted in an orange box.
- Carbon (C)**: Atomic number 6, highlighted in a teal box.
- Silicon (Si)**: Atomic number 14, highlighted in an orange box.
- Copper (Cu)**: Atomic number 29, highlighted in a light green box.
- Tungsten (W)**: Atomic number 74, highlighted in a light green box.
- Gold (Au)**: Atomic number 79, highlighted in a light green box.

A lot of elements to play with...

Deposition with fs-PLD:

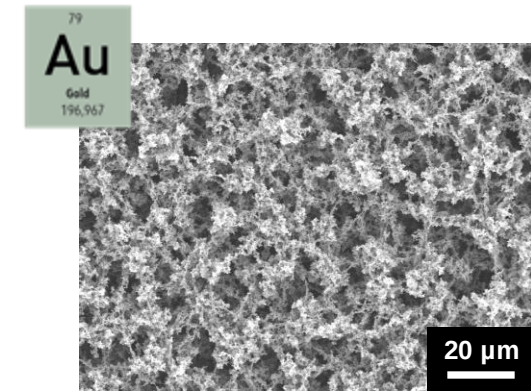
- Same fluence, 0.1 J/cm²
- Different pressure



The image shows a periodic table of elements. Several elements are highlighted in colored boxes, likely representing the components of the 'Seven Wonders of the World' mentioned in the text. The highlighted elements are:

- H** (Hydrogen, 1) - Light blue box
- B** (Boron, 5) - Orange box
- C** (Carbon, 6) - Teal box
- Na** (Sodium, 11) - Light blue box
- Mg** (Magnesium, 12) - Light blue box
- Si** (Silicon, 14) - Orange box
- Cu** (Copper, 29) - Teal box
- W** (Tungsten, 74) - Teal box
- Au** (Gold, 79) - Teal box

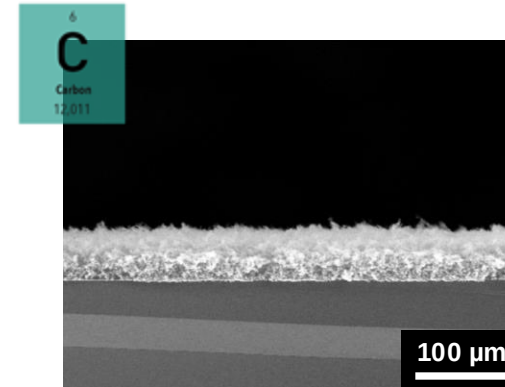
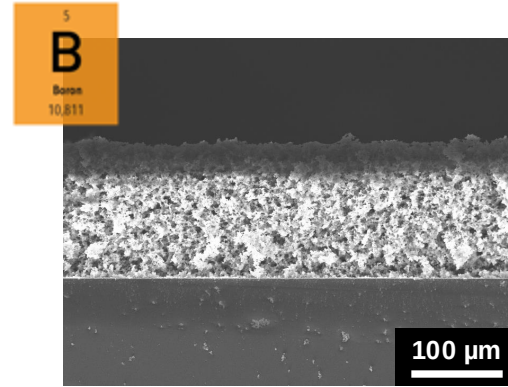
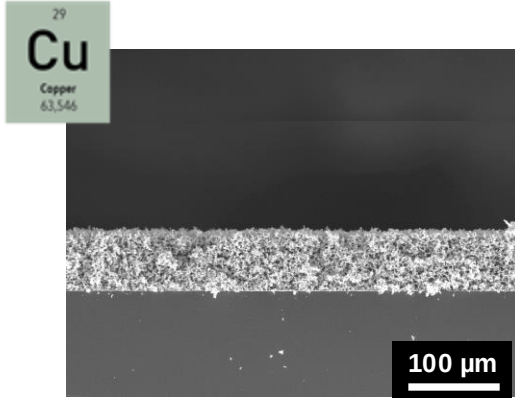
The rest of the periodic table is shown in a standard color scheme with various shades of blue, green, and orange.



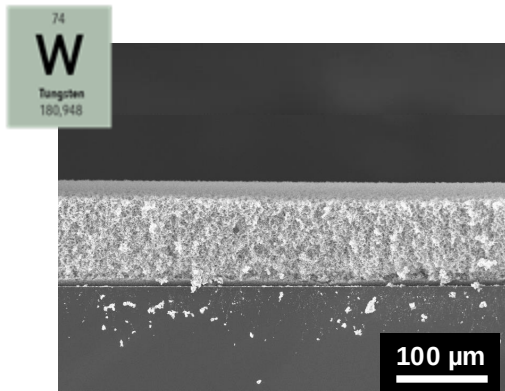
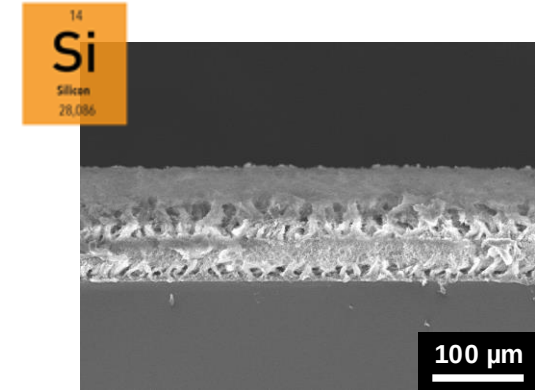
A lot of elements to play with...

Deposition with fs-PLD:

- Same fluence, 0.1 J/cm²
- Different pressure

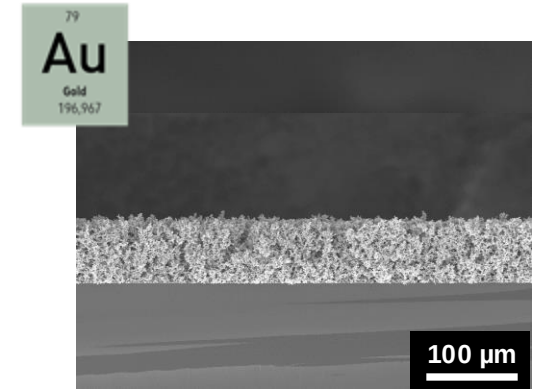


Thickness > 100 μm



The image shows a periodic table of elements. Five elements are highlighted with colored boxes and their names are written in German:

- Boron (B)**: Atomic number 5, highlighted in orange.
- Carbon (C)**: Atomic number 6, highlighted in teal.
- Silicon (Si)**: Atomic number 14, highlighted in orange.
- Copper (Cu)**: Atomic number 29, highlighted in grey.
- Tungsten (W)**: Atomic number 74, highlighted in grey.



Foam properties control

Nano-scale

- Crystalline structure & composition
- Nanoparticle size

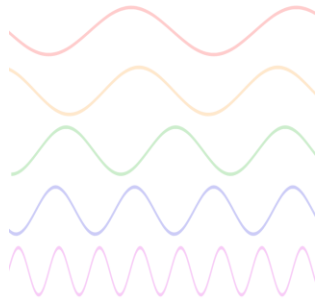
Micro-scale

- Aggregate size
- Morphology

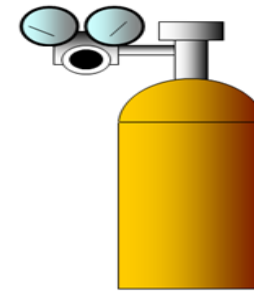
Macro-scale

- Uniformity
- Thickness profile

Pulse Duration

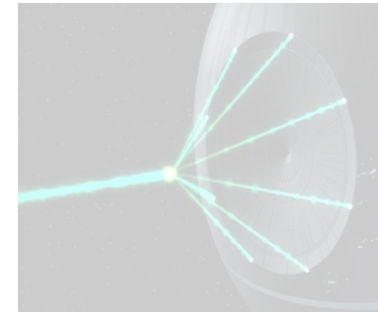


Target composition



Gas pressure

Laser Fluence

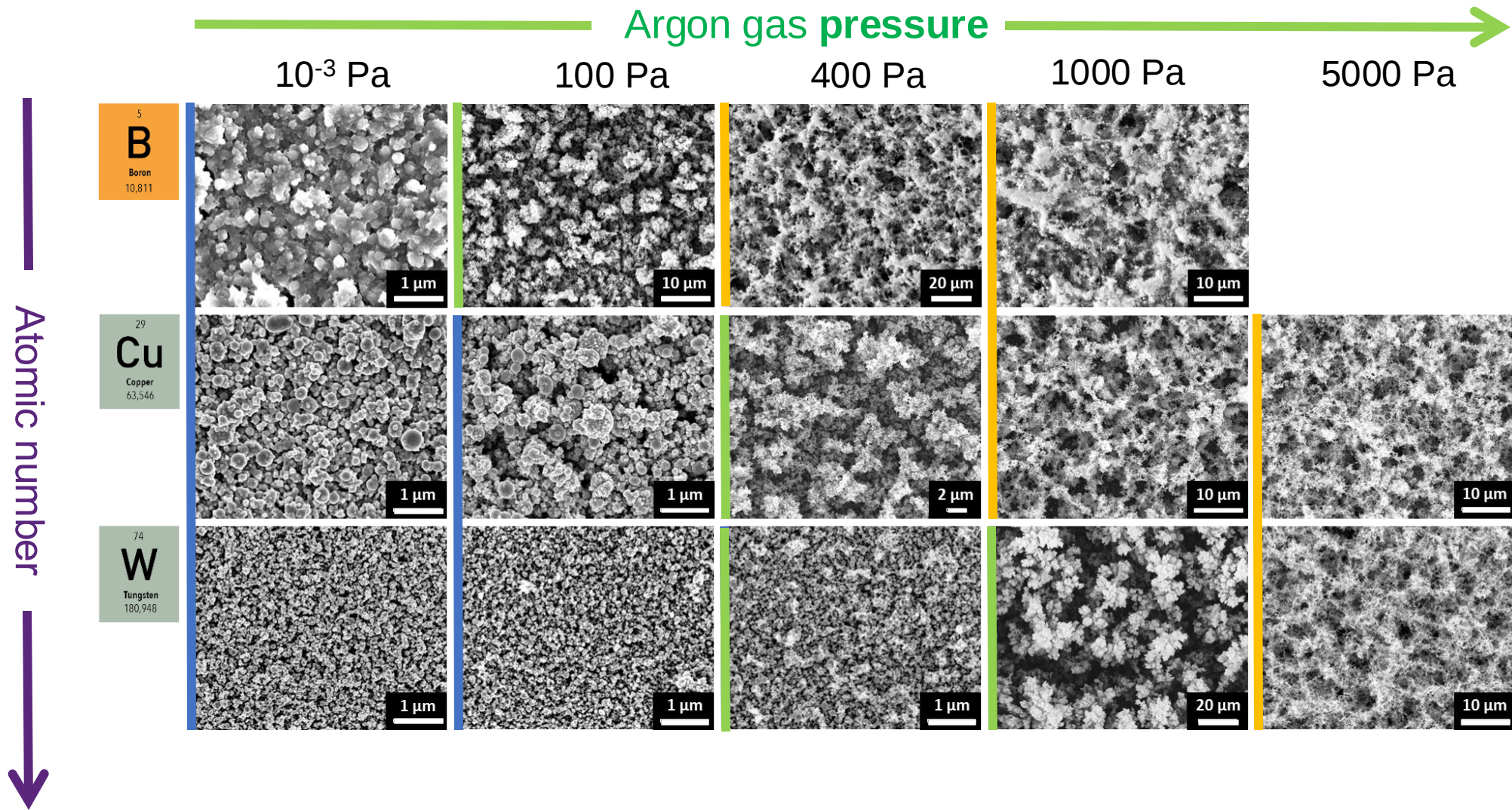


Deposition time

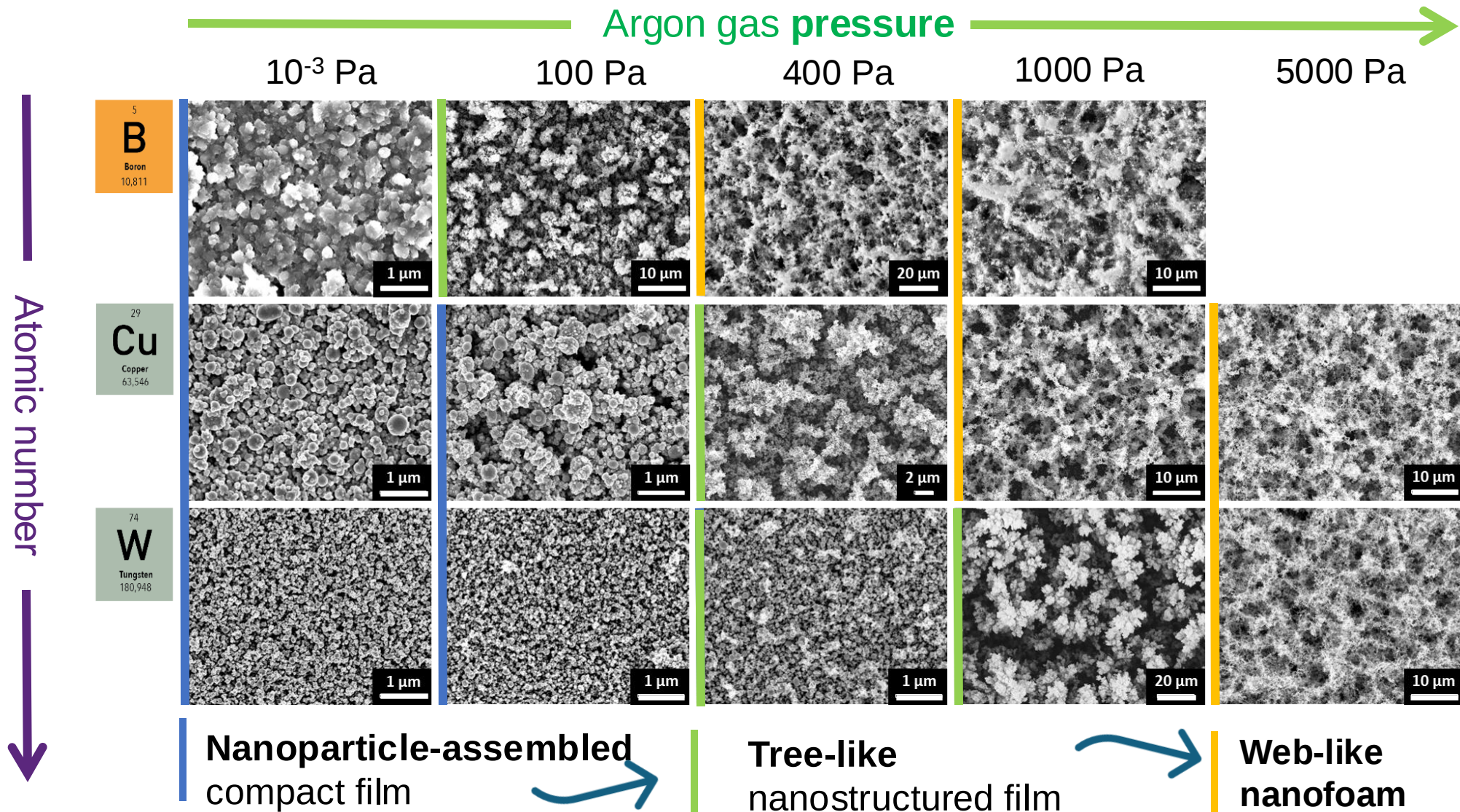


PLD process parameters

Fine tuning of nanofoam morphology



Fine tuning of nanofoam morphology



Synthesis, **characterization** and testing of hydrogenated boron nanofoams for laser-driven proton-boron fusion

Nanofoam characterization

Integration of:

- Scanning Electron Microscopy

Information on:

- Morphology
- Thickness d

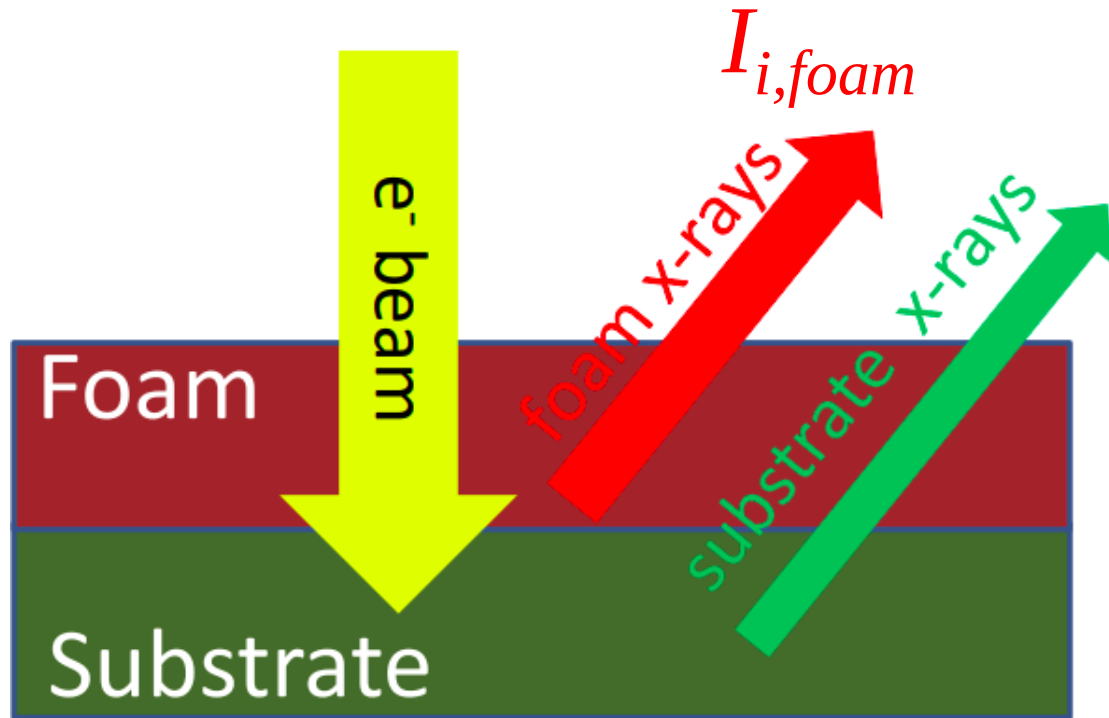
Nanofoam characterization

Integration of:

- Scanning Electron Microscopy
- Energy Dispersive X-Ray Spectroscopy

Information on:

- Morphology
- Thickness d
- Composition c_i



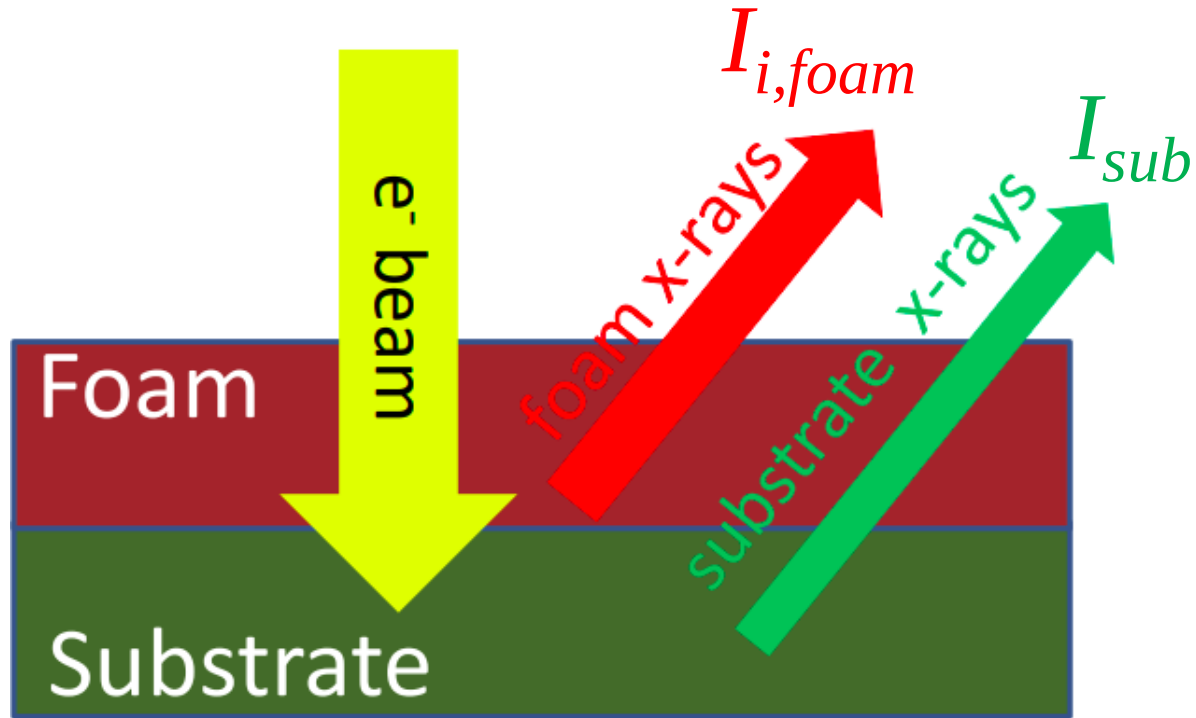
Nanofoam characterization

Integration of:

- Scanning Electron Microscopy
- Energy Dispersive X-Ray Spectroscopy
- EDDIE model

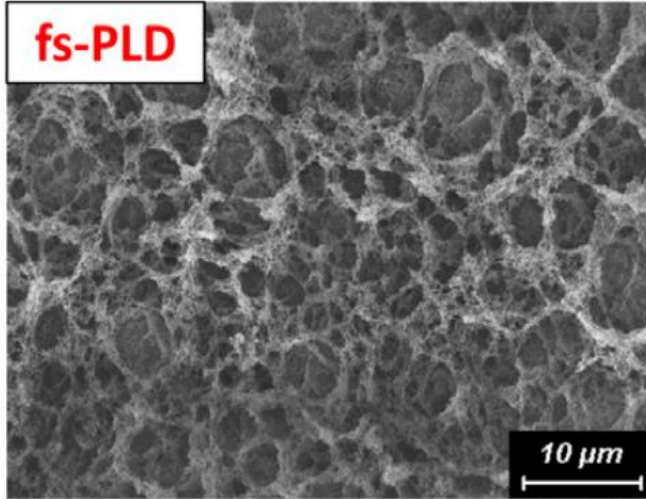
Information on:

- Morphology
- Thickness d
- Composition c_i
- Mass density ρ

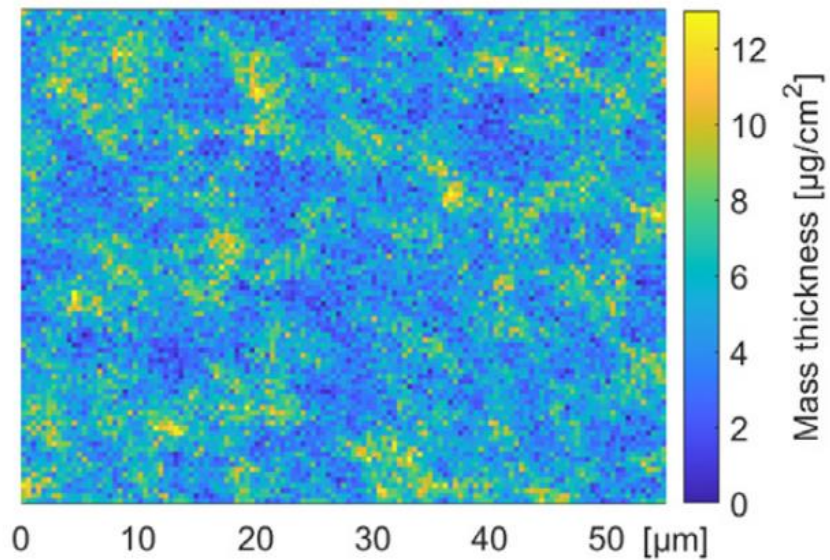
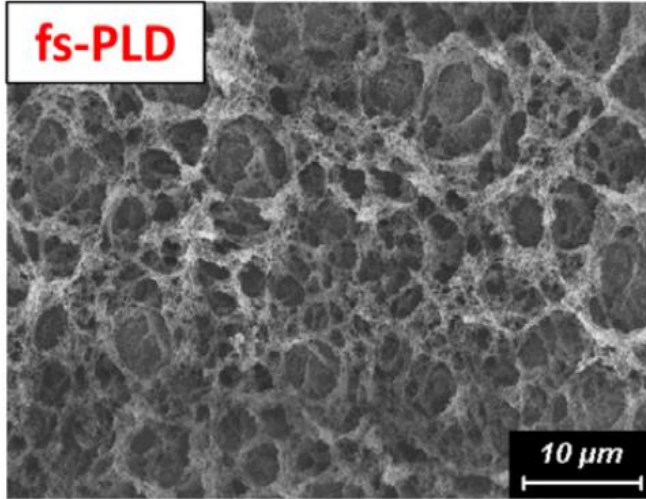


$$\frac{I_{i,foam}}{I_{sub}} = f(\rho, d, c_i, c_{i \neq j})$$

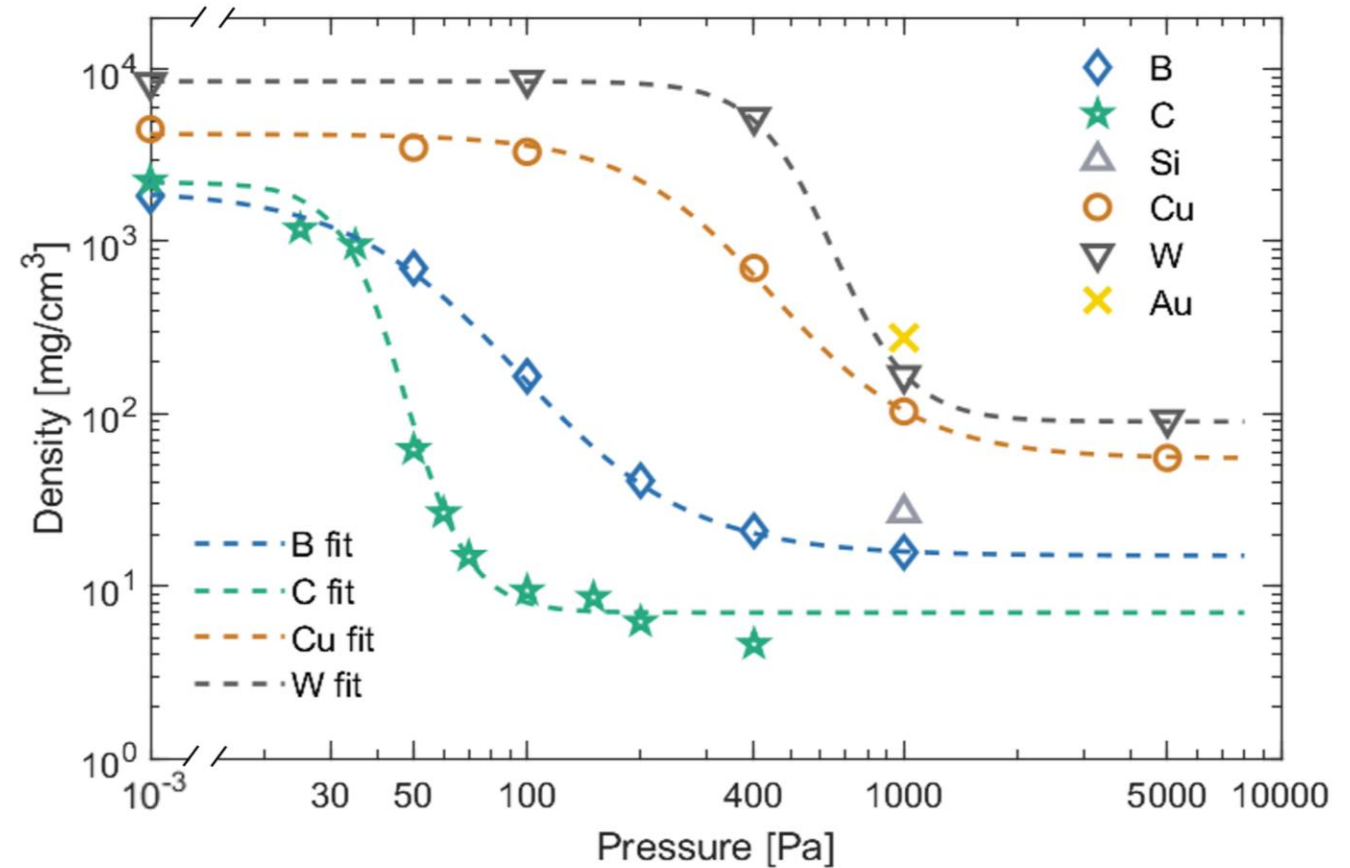
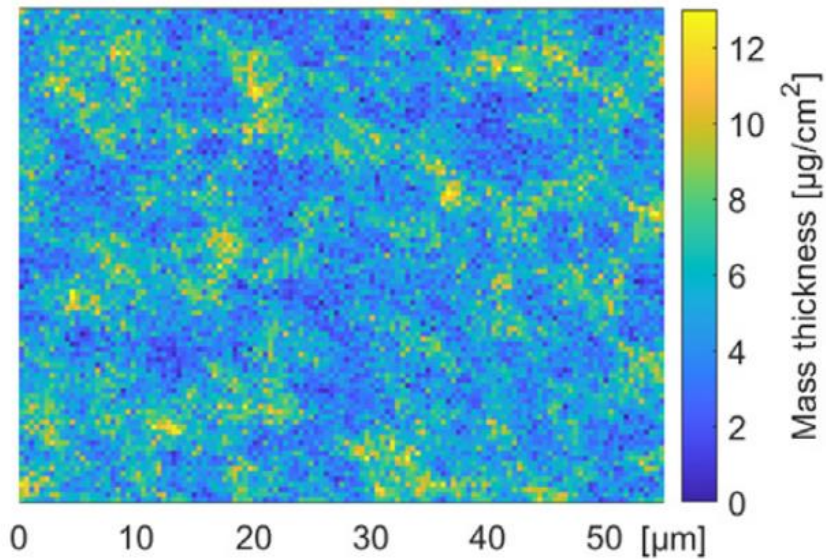
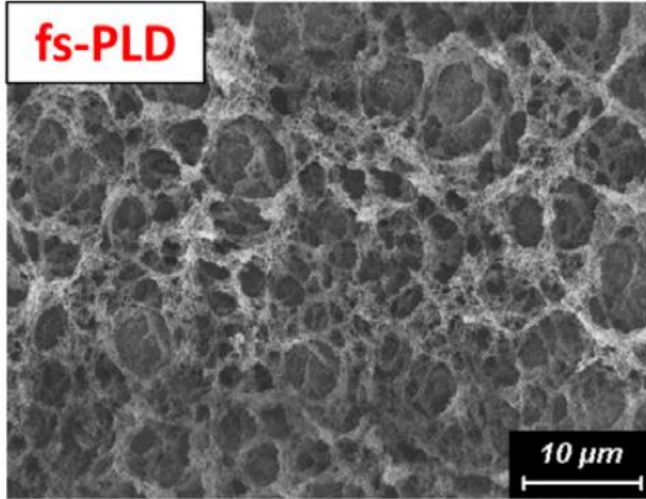
Fine tuning of nanofoam density



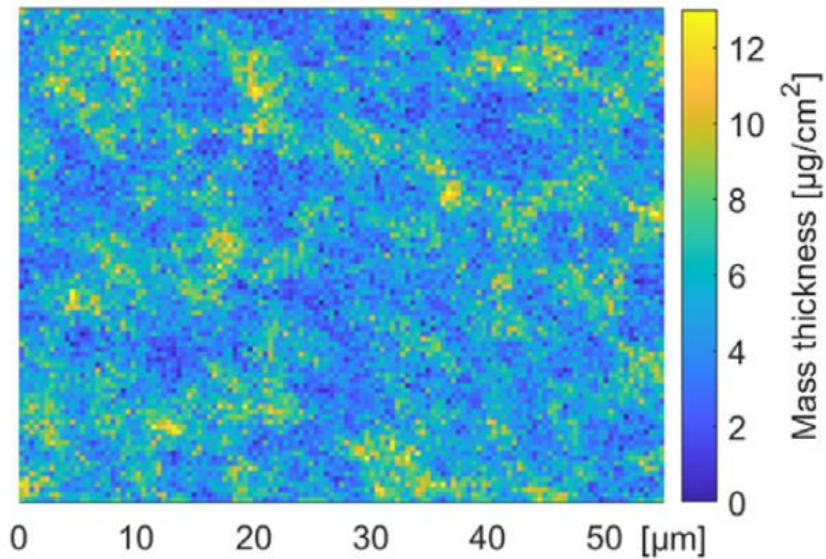
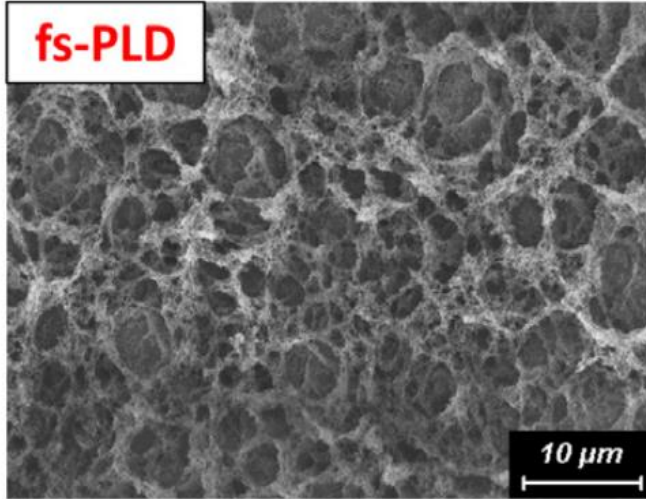
Fine tuning of nanofoam density



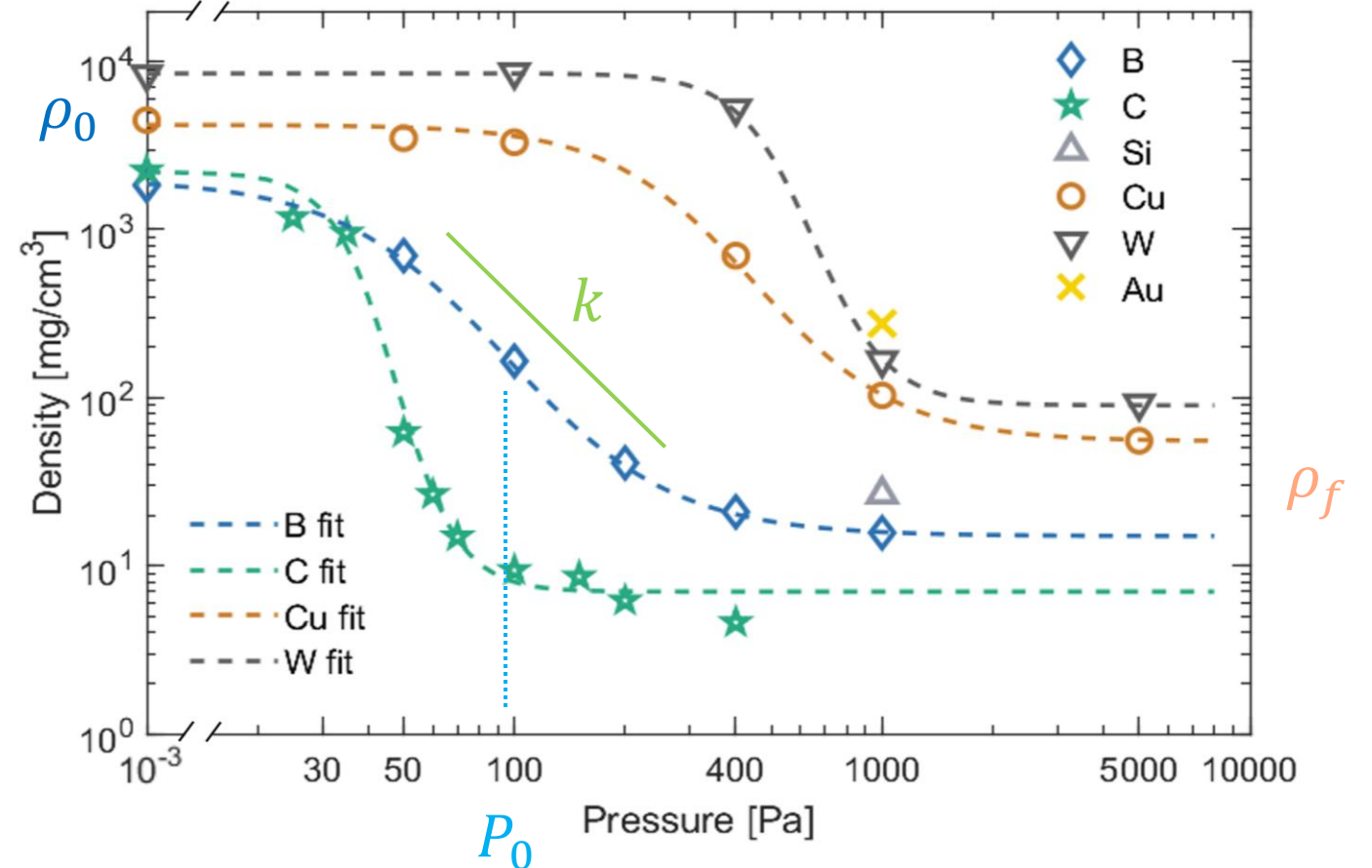
Fine tuning of nanofoam density



Fine tuning of nanofoam density



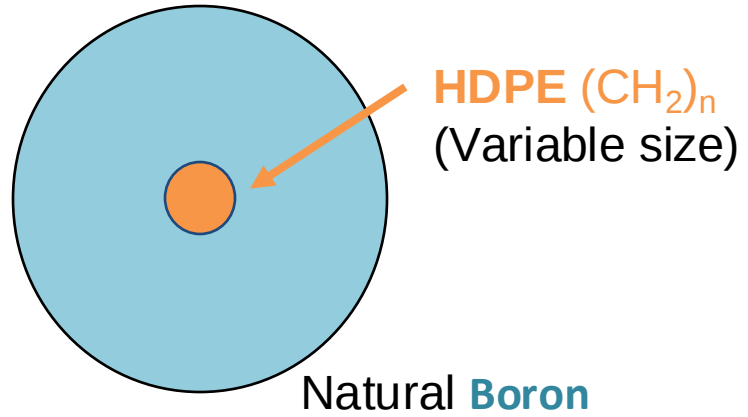
$$\rho(P) = \rho_0 \left(\frac{\rho_f}{\rho_0} \right)^{\left[\frac{P^k}{P^k + P_0^k} \right]}$$



Synthesis, characterization and testing of **hydrogenated boron nanofoams** for laser-driven proton-boron fusion

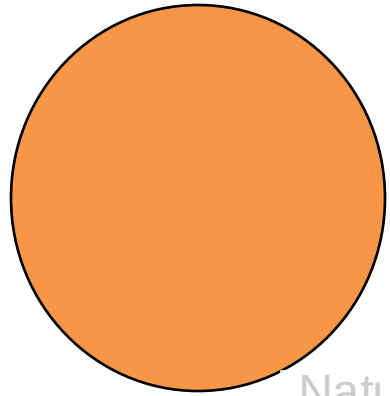
Hydrogenated born nanofoams

Heterogeneous target



Hydrogenated born nanofoams

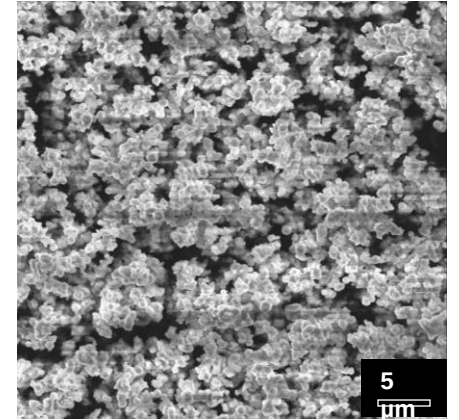
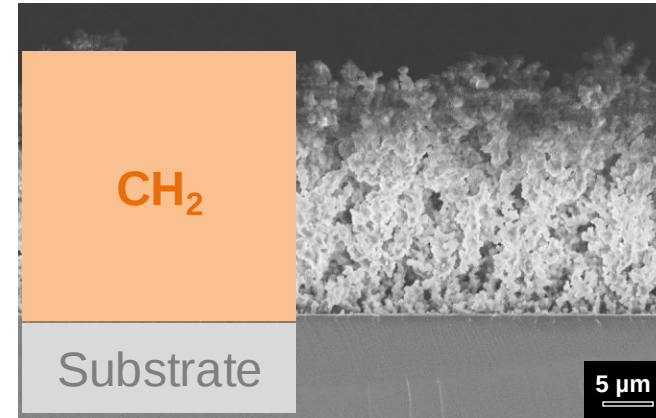
Heterogeneous target



HDPE (CH₂)_n
(Variable size)

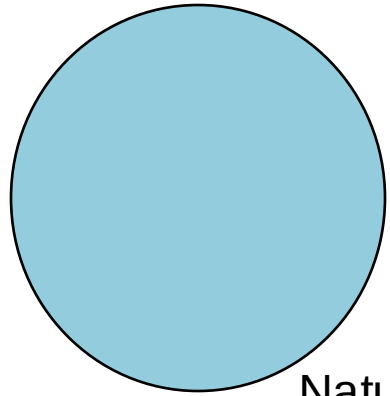
Natural Boron

CH₂ nanofoam



Hydrogenated born nanofoams

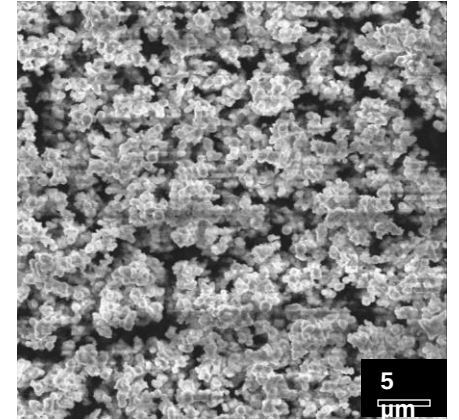
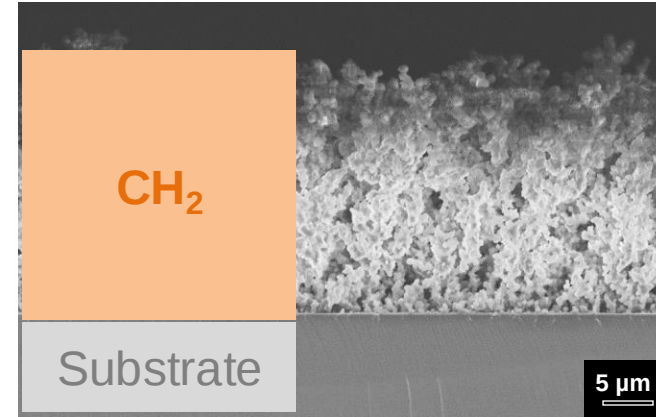
Heterogeneous target



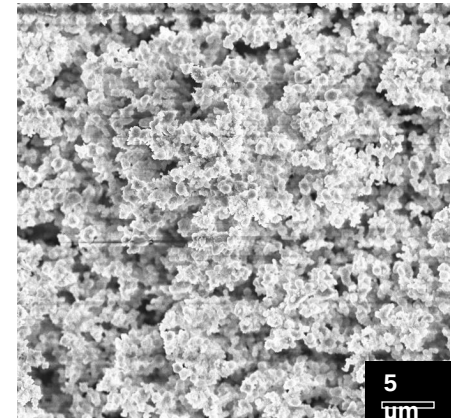
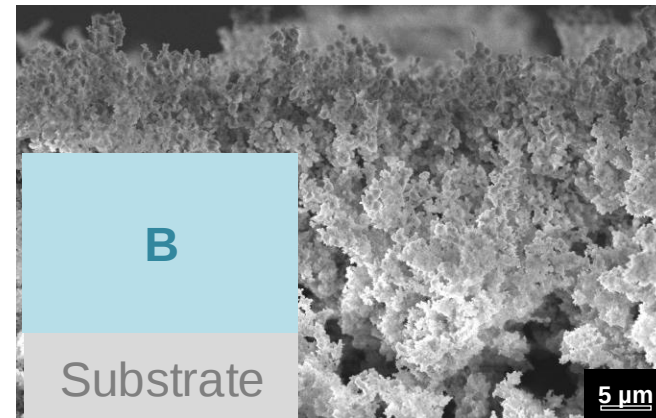
HDPE (CH₂)_n
(Variable size)

Natural **Boron**

CH₂ nanofoam

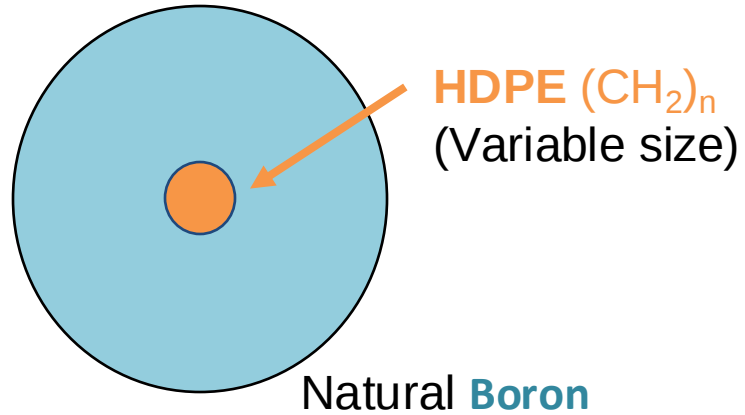


B multilayer

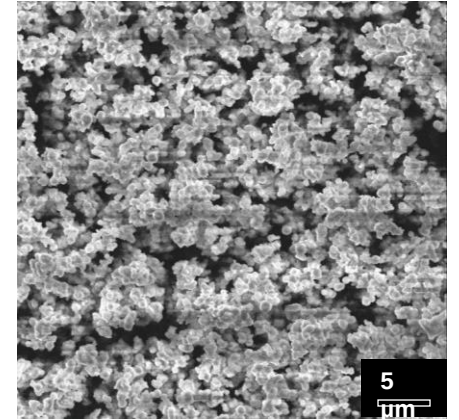
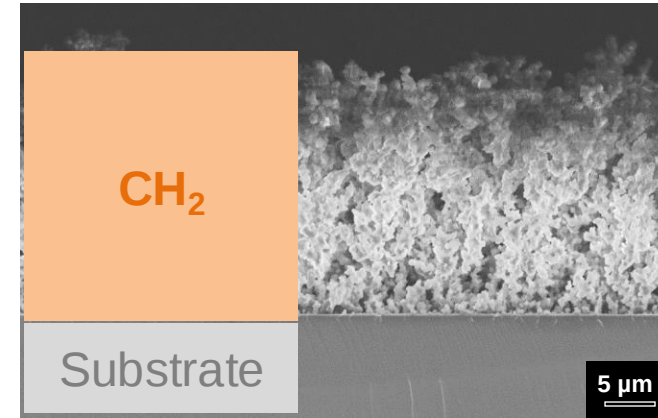


Hydrogenated born nanofoams

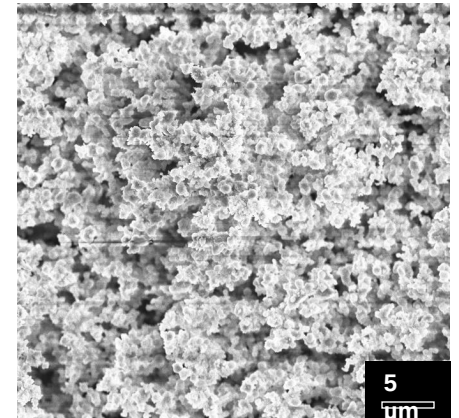
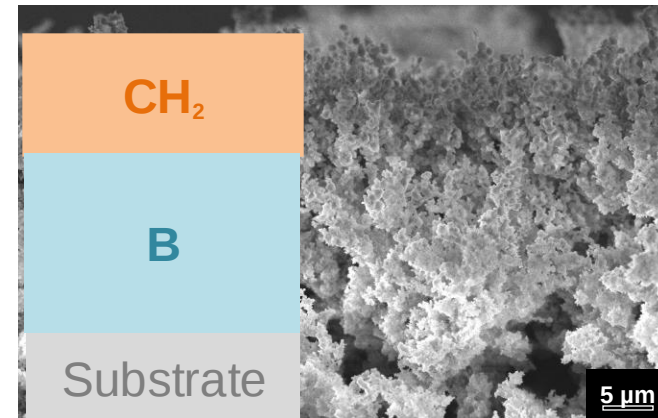
Heterogeneous target



CH₂ nanofoam

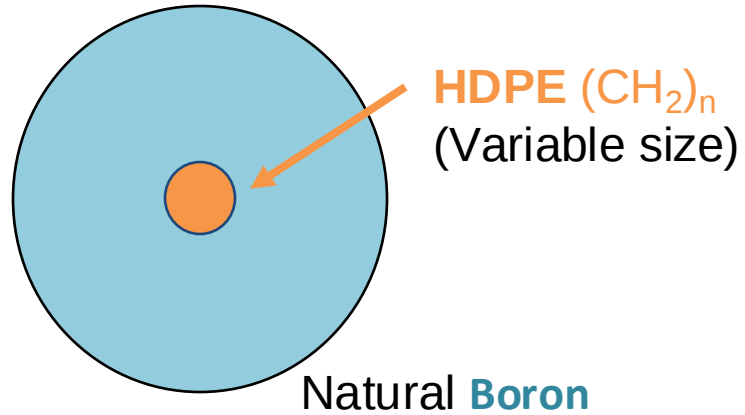


B / CH₂ multilayer

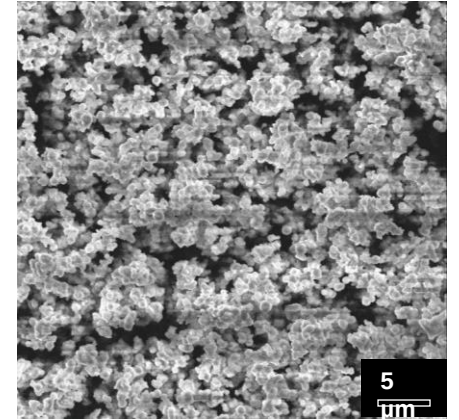
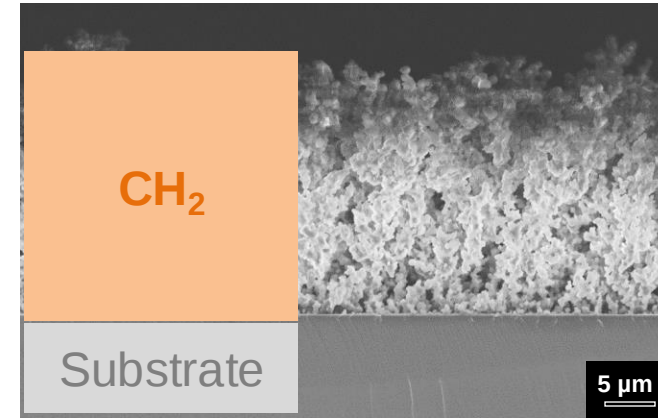


Hydrogenated born nanofoams

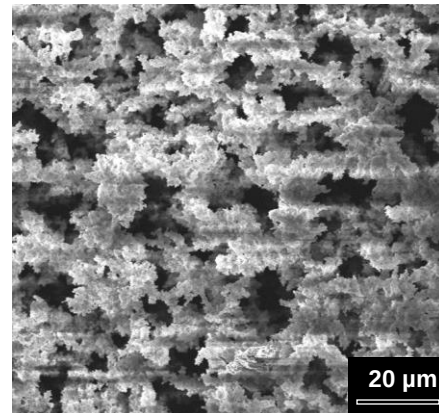
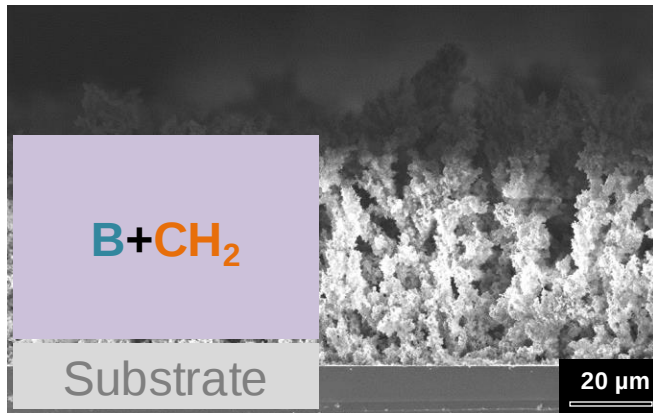
Heterogeneous target



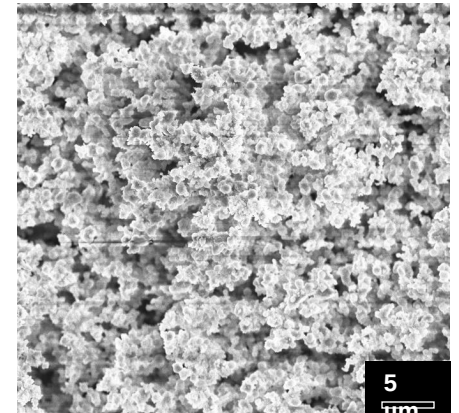
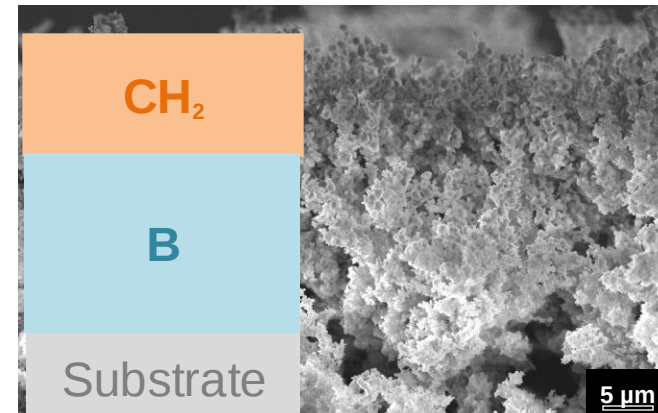
CH₂ nanofoam



B+CH₂ nanofoam



B / CH₂ multilayer

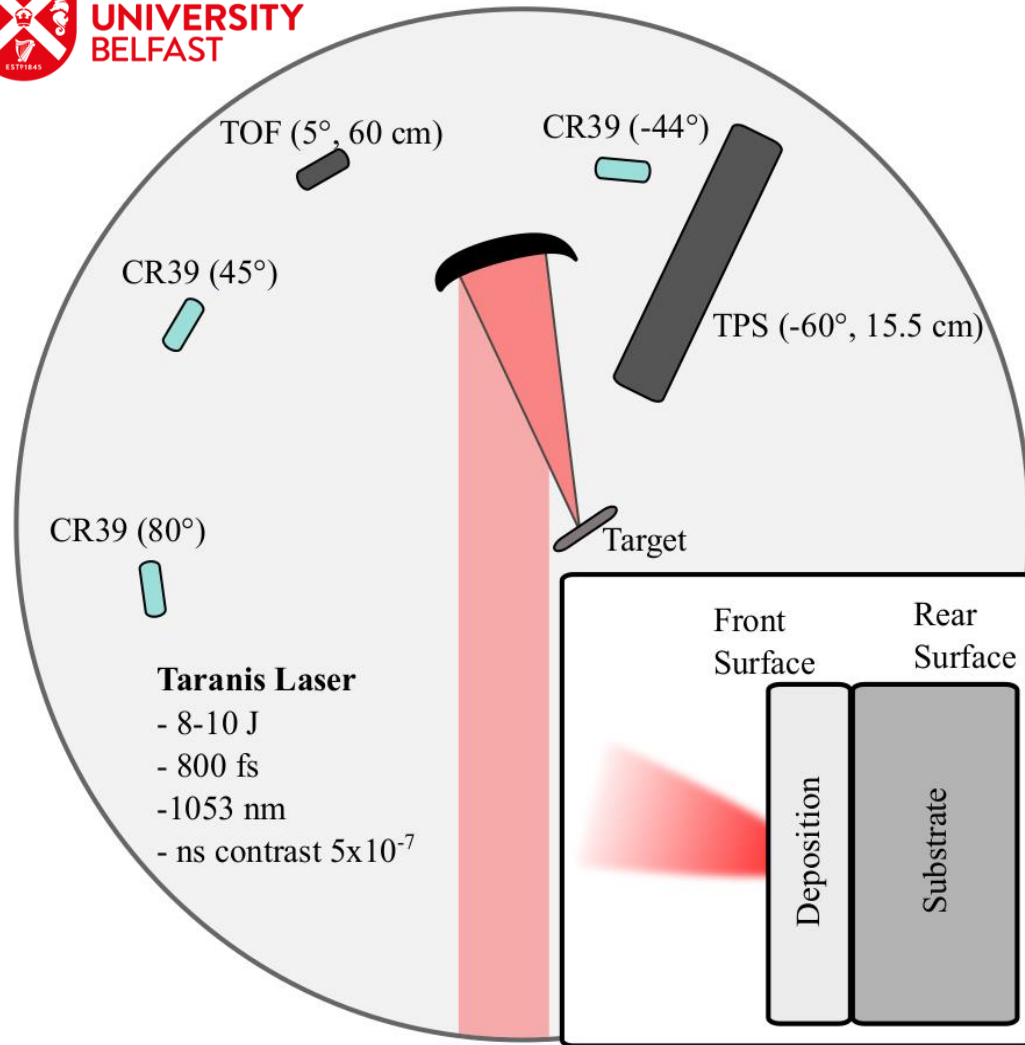


Synthesis, characterization and **testing** of **hydrogenated boron nanofoams** for laser-driven **proton-boron fusion**

Nanofoams targets for experiment @ Taranis



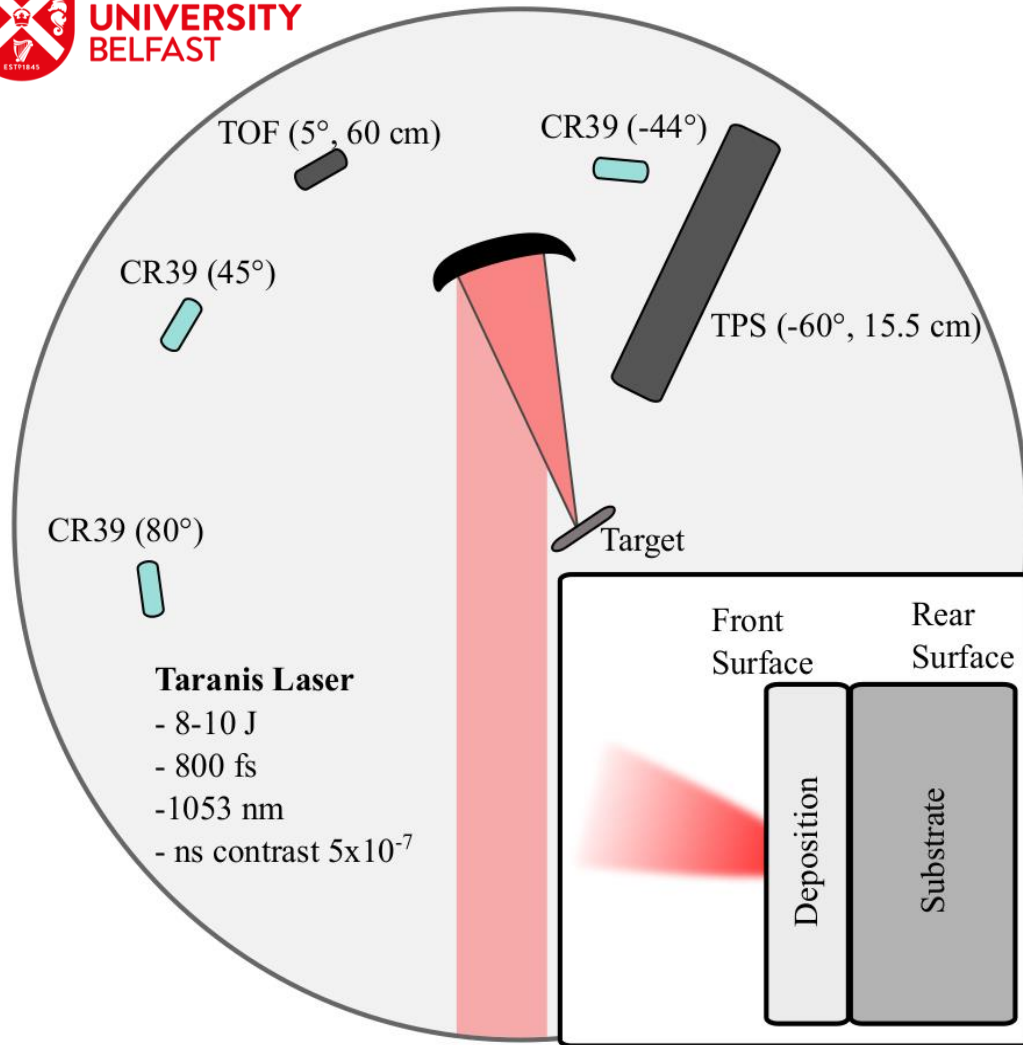
QUEEN'S
UNIVERSITY
BELFAST



Nanofoams targets for experiment @ Taranis



QUEEN'S
UNIVERSITY
BELFAST



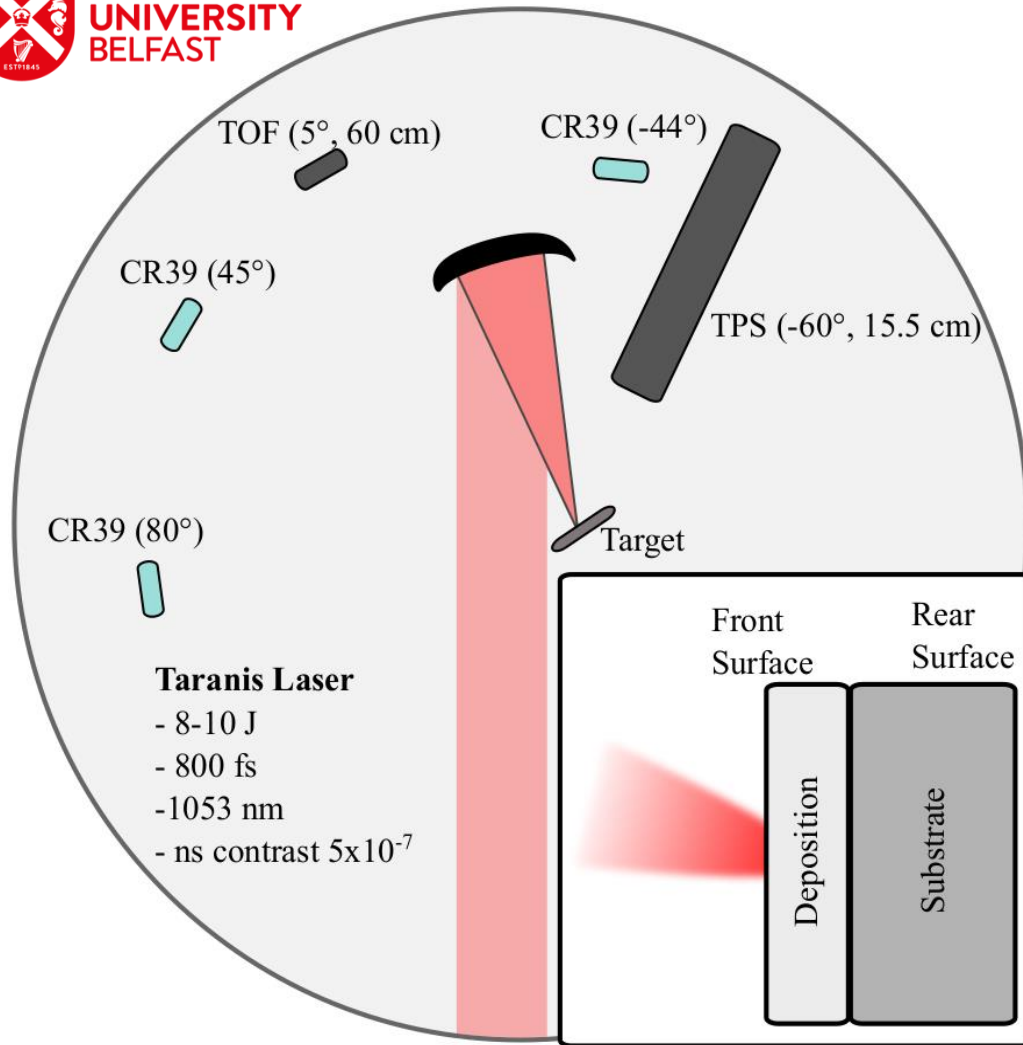
CH₂ nanofoam
on BN substrate

120 mg/cm ³ 10 μm	120 mg/cm ³ 20 μm
BN	BN
~60% H, ~30% C, ~10% O	

Nanofoams targets for experiment @ Taranis



QUEEN'S
UNIVERSITY
BELFAST



CH₂ nanofoam
on BN substrate

120 mg/cm ³ 10 μm	120 mg/cm ³ 20 μm
BN	BN
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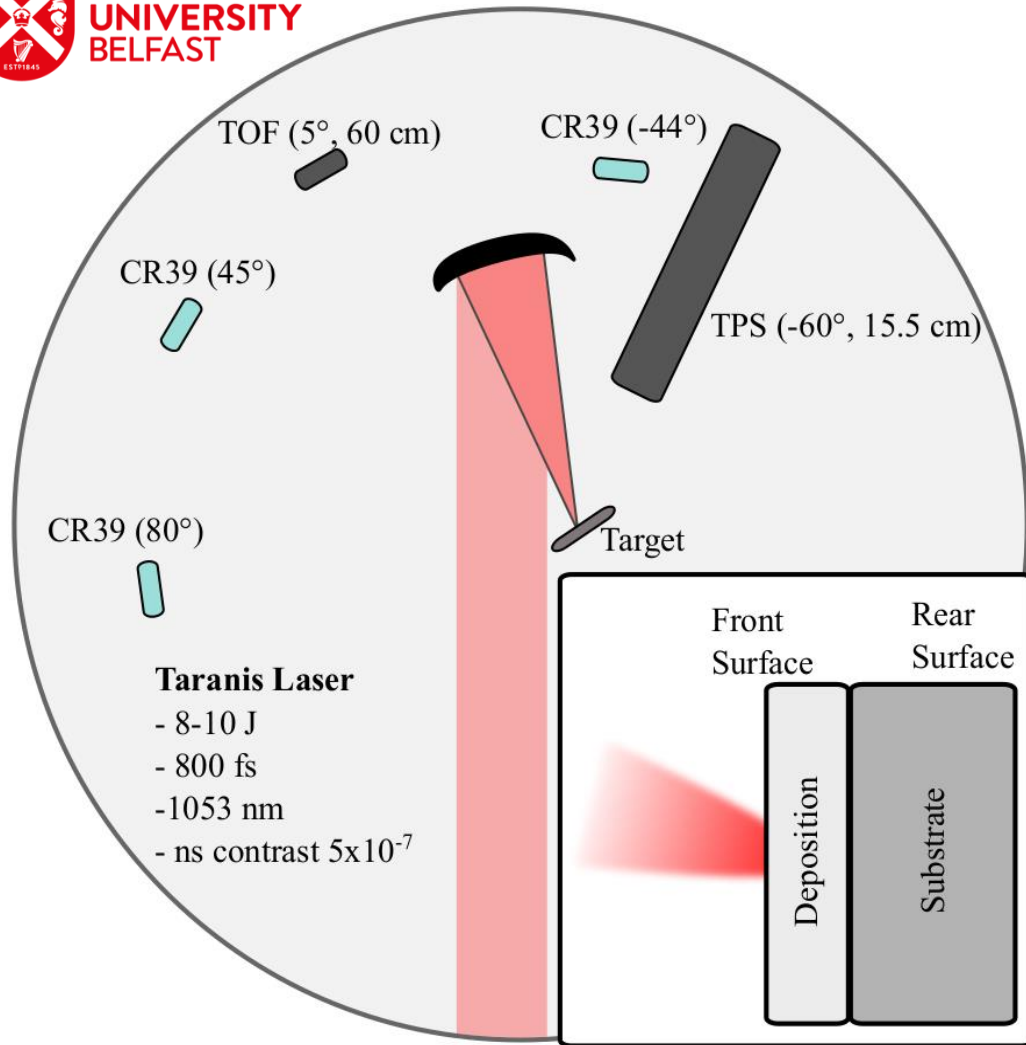
B nanofoam
on PP substrate

100 mg/cm ³ 50 μm	100 mg/cm ³ 100 μm	50 mg/cm ³ 100 μm
PP	PP	PP
~85-90% B, ~10-15% O		

Nanofoams targets for experiment @ Taranis



QUEEN'S
UNIVERSITY
BELFAST



CH₂ nanofoam
on BN substrate

120 mg/cm ³ 10 μm	120 mg/cm ³ 20 μm
BN	BN
~60% H, ~30% C, ~10% O	

B nanofoam
on PP substrate

100 mg/cm ³ 50 μm	100 mg/cm ³ 100 μm	50 mg/cm ³ 100 μm
PP	PP	PP
~85-90% B, ~10-15% O		

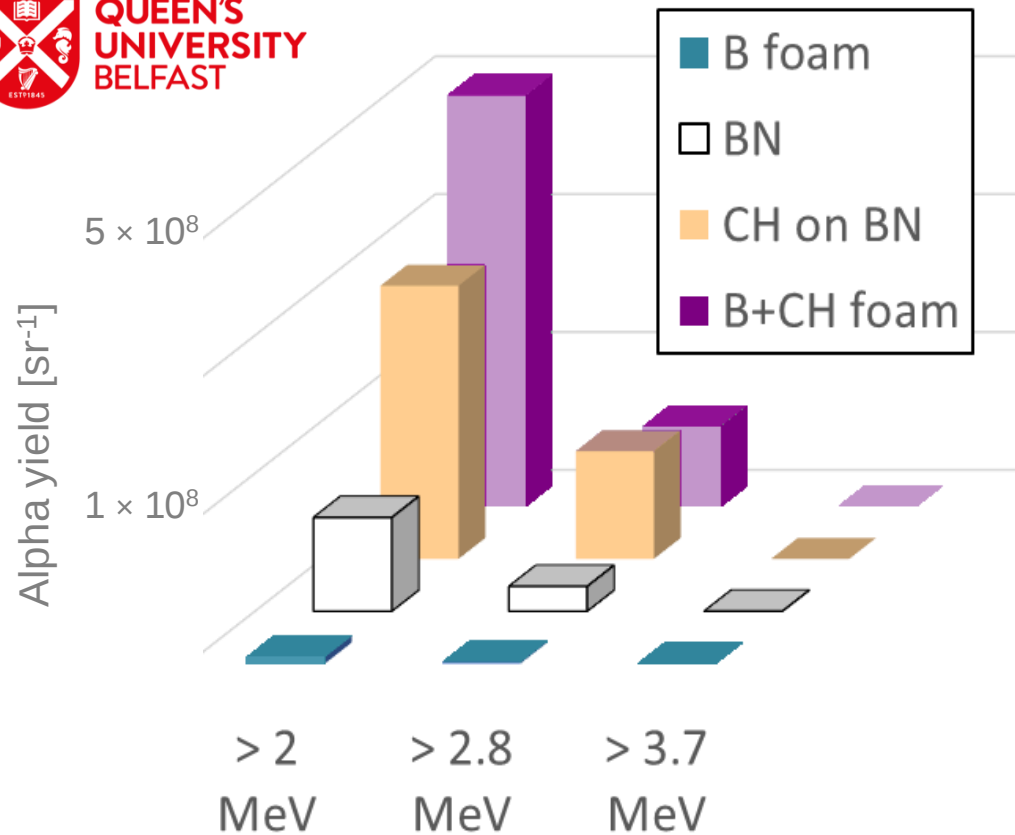
B+CH₂ nanofoam
on PP substrate

80 mg/cm ³ 60 μm	40 mg/cm ³ 100 μm
PP	PP
~40% H, ~30% B, ~20% C, ~10% O	

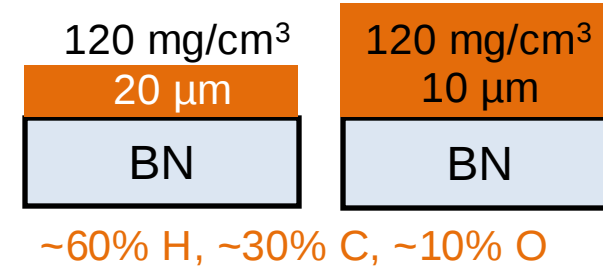
Nanofoams targets for experiment @ Taranis



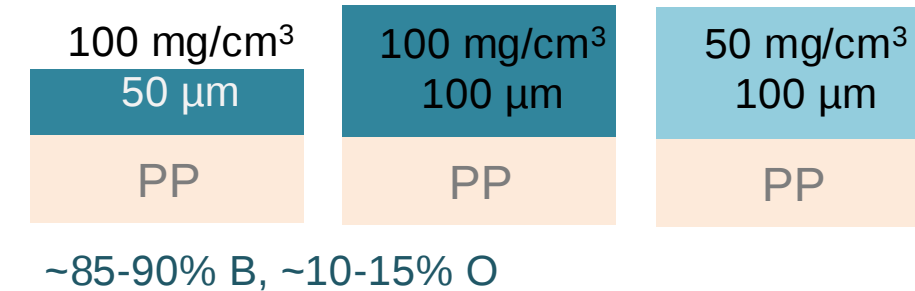
QUEEN'S
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BELFAST



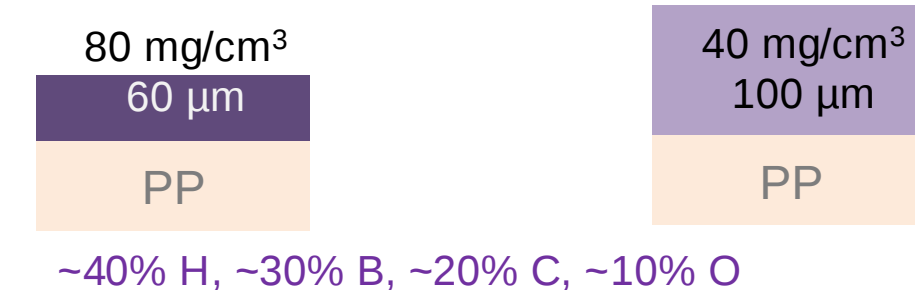
CH₂ nanofoam
on BN substrate



B nanofoam
on PP substrate



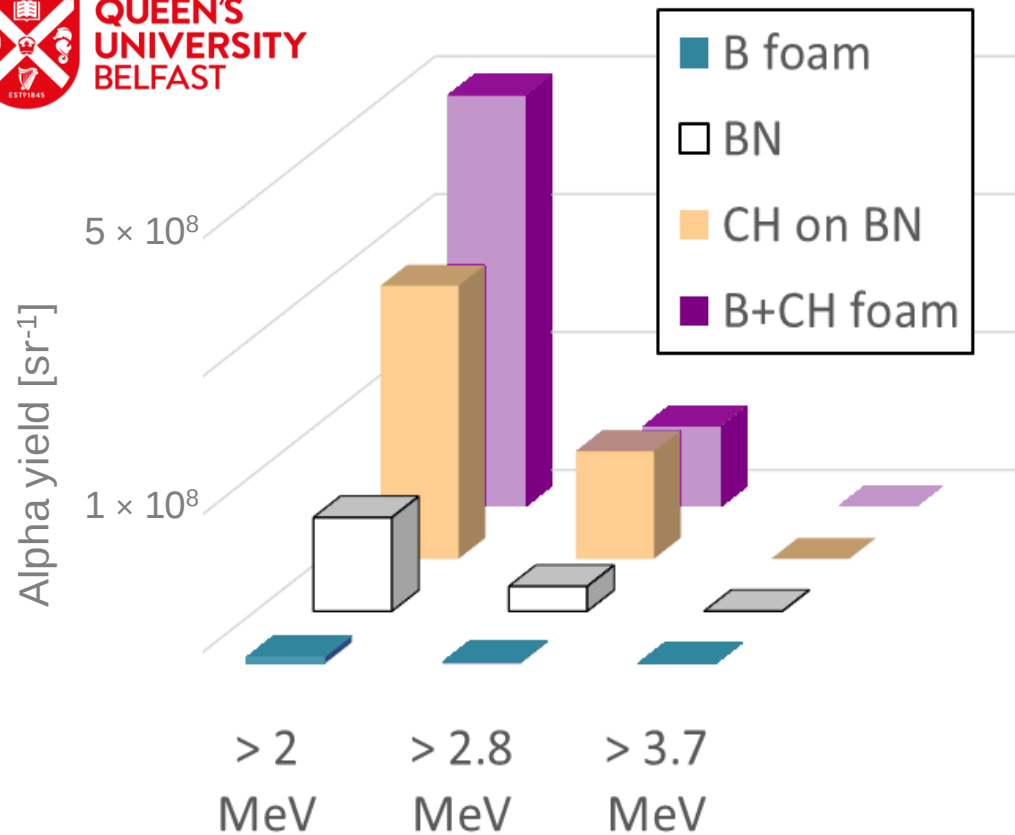
B+CH₂ nanofoam
on PP substrate



Nanofoams targets for experiment @ Taranis

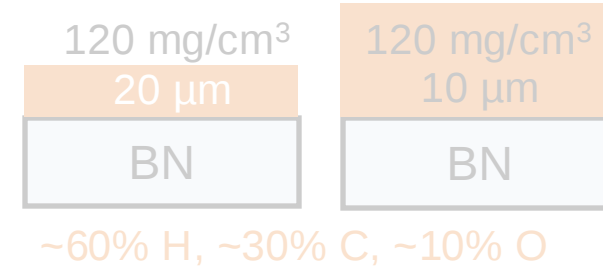


QUEEN'S
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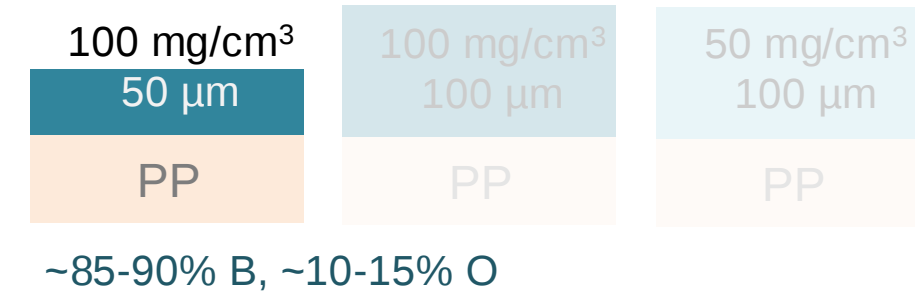


In-foam proton-boron
fusion reactions

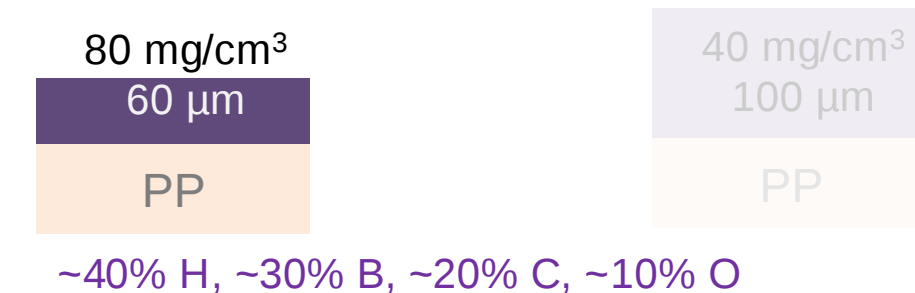
CH₂ nanofoam
on BN substrate



B nanofoam
on PP substrate



B+CH₂ nanofoam
on PP substrate



In conclusion

Nano-scale

- Crystalline structure & composition
- Nanoparticle size

Micro-scale

- Aggregate size
- Morphology

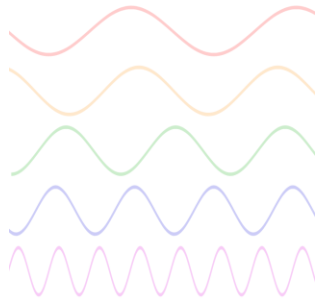
Macro-scale

- Uniformity
- Thickness profile

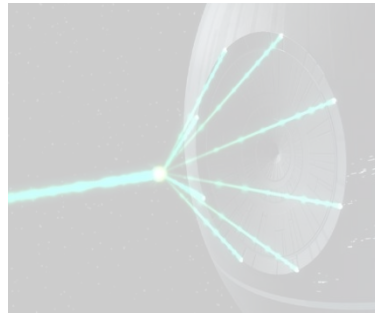


Unparalleled versatility

Pulse Duration



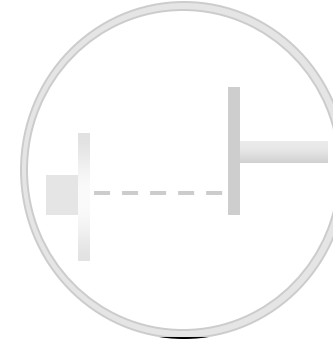
Laser Fluence



Gas pressure



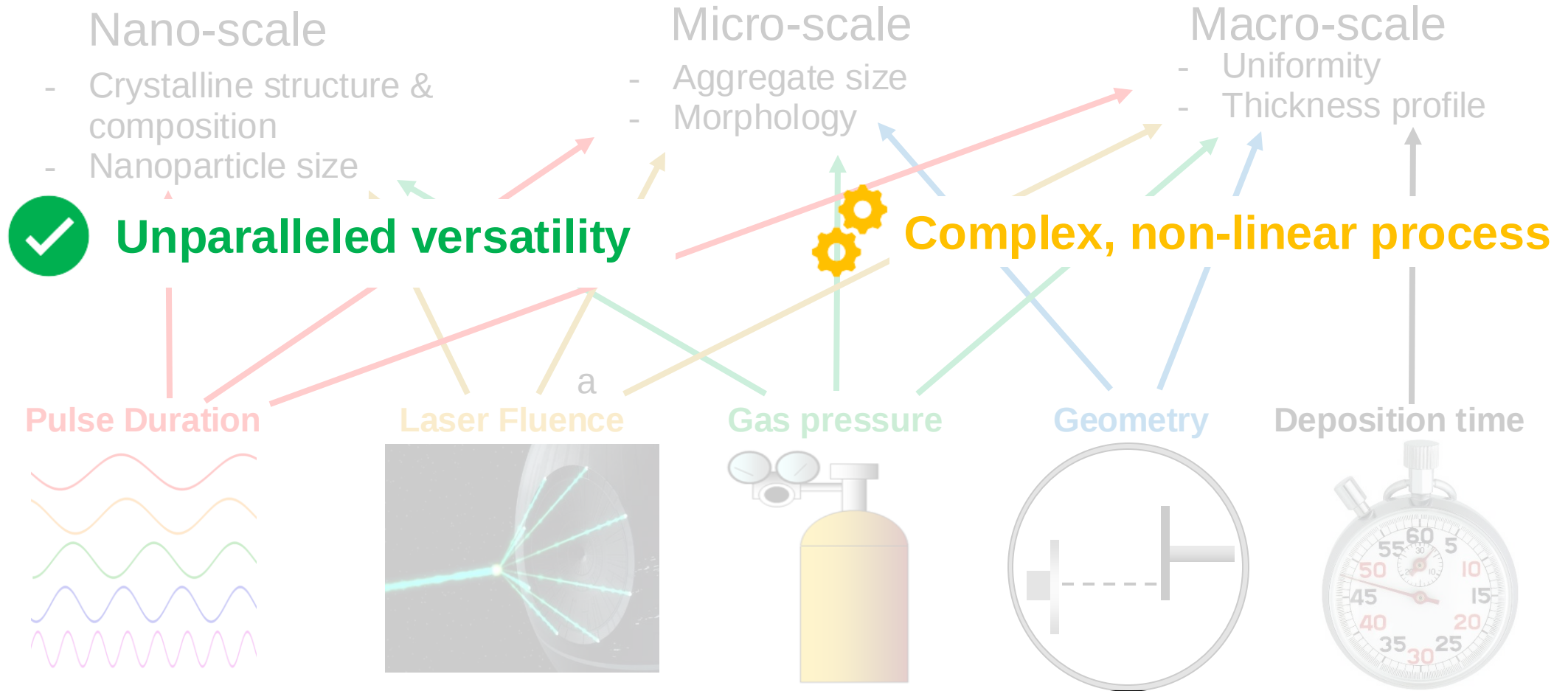
Geometry



Deposition time



In conclusion



In conclusion

Nano-scale

- Crystalline structure & composition
- Nanoparticle size

Micro-scale

- Aggregate size
- Morphology

Macro-scale

- Uniformity
- Thickness profile

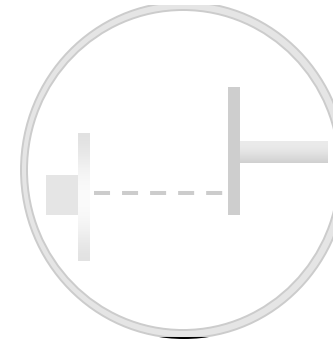
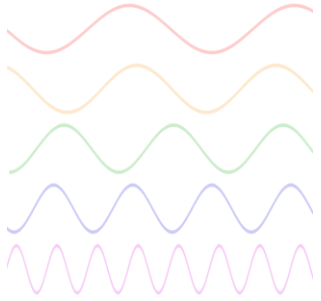


Unparalleled versatility

Complex, non-linear process

Potential for many applications

Pulse Duration



Position time



The periodic table is color-coded by groups. The groups are numbered 1 through 18. The colors are: Group 1 (H, Li, Na, K, Rb, Cs, Fr) is light blue; Group 2 (Be, Mg, Ca, Sr, Ba, Ra) is light green; Groups 3-10 (Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr) are light purple; Group 11 (Ag, Au, Hg) is light orange; Group 12 (Cd, In, Sn, Sb, Te, I, Xe) is light yellow; Group 13 (B, Al, Ga, In, Tl) is light green; Group 14 (C, Si, Ge, Sn, Pb) is light blue; Group 15 (N, P, As, Sb, Bi) is light orange; Group 16 (O, S, Se, Te, Po) is light green; Group 17 (F, Cl, Br, I, At) is light blue; Group 18 (He, Ne, Ar, Kr, Xe, Rn) is light orange. The lanthanide and actinide series are shown below the main table, color-coded by their respective groups.

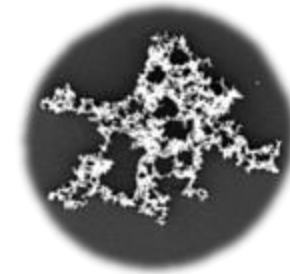
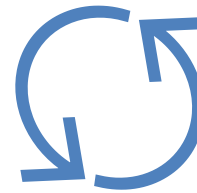
Explore other elements & **compounds**
(e.g. Boranes, see M. Londesborough's talk)

...What is coming next

1

Explore other elements & **compounds**
(e.g. Boranes, see M. Londesborough's talk)

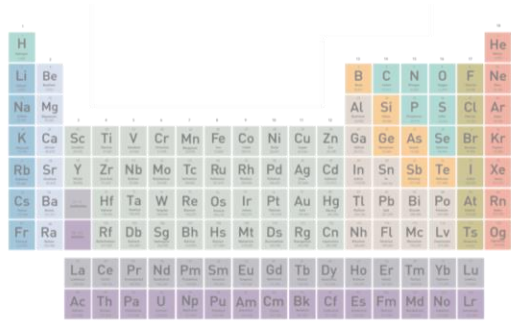
2



Nanofoam **optimization** according to laser parameters

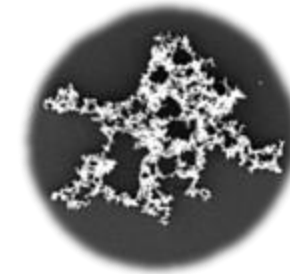
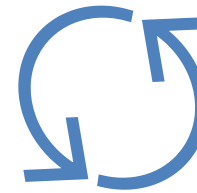
...What is coming next

1

A standard periodic table of elements, color-coded by groups. It includes elements from Hydrogen (H) to Oganesson (Og).

Explore other elements & **compounds**
(e.g. Boranes, see M. Londesborough's talk)

2



Nanofoam **optimization** according to laser parameters

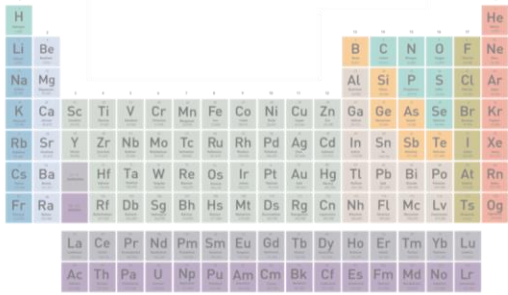
3



Advanced targets for future **experiments**

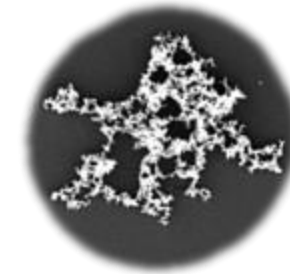
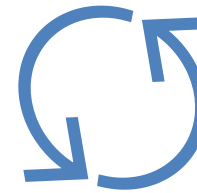
...What is coming next

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A standard periodic table of elements, color-coded by groups. It includes elements from Hydrogen (H) to Oganesson (Og).

Explore other elements & **compounds**
(e.g. Boranes, see M. Londesborough's talk)

2



Nanofoam **optimization** according to laser parameters

3



Advanced targets for future **experiments**

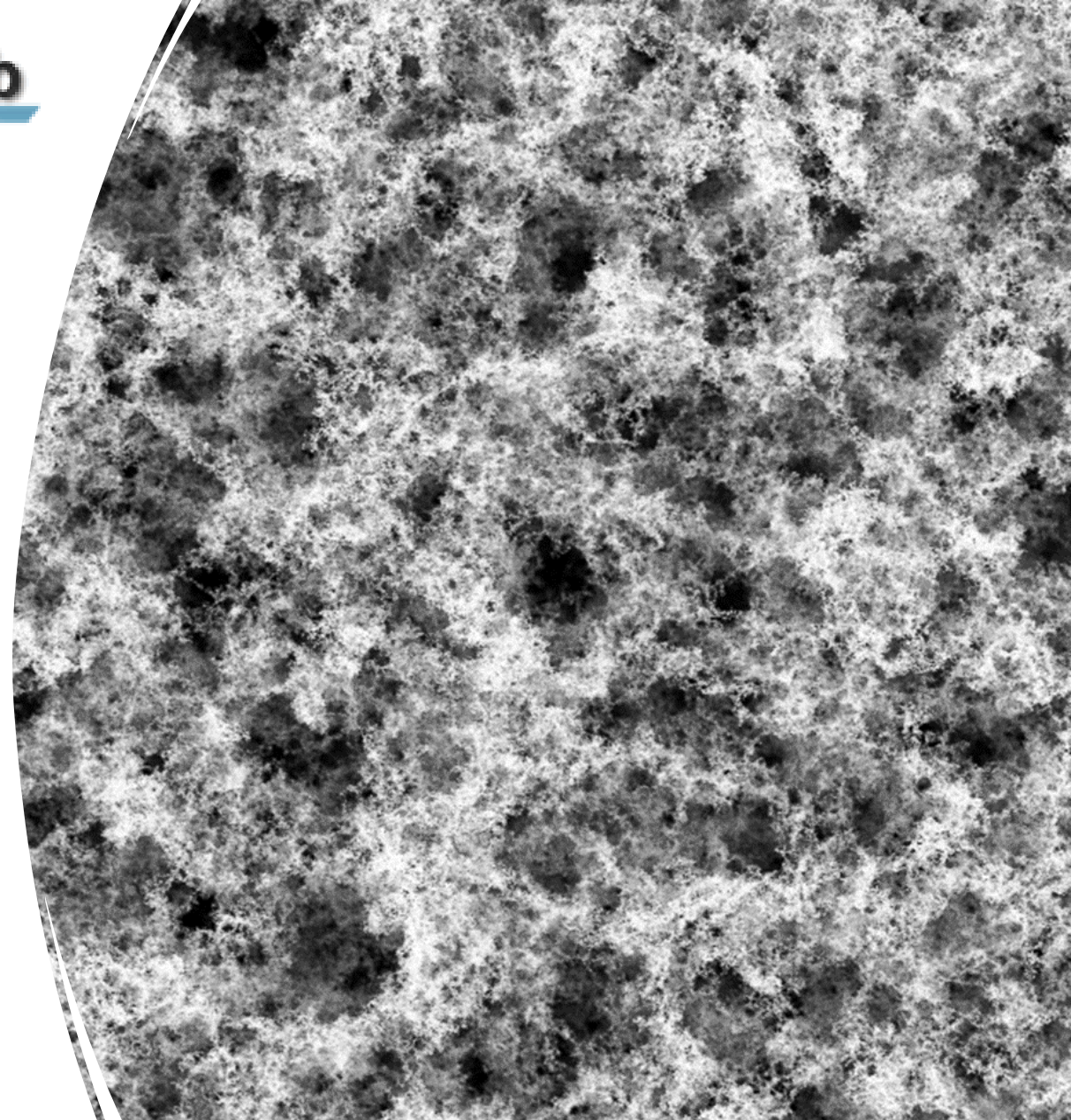


4

Your suggestions!

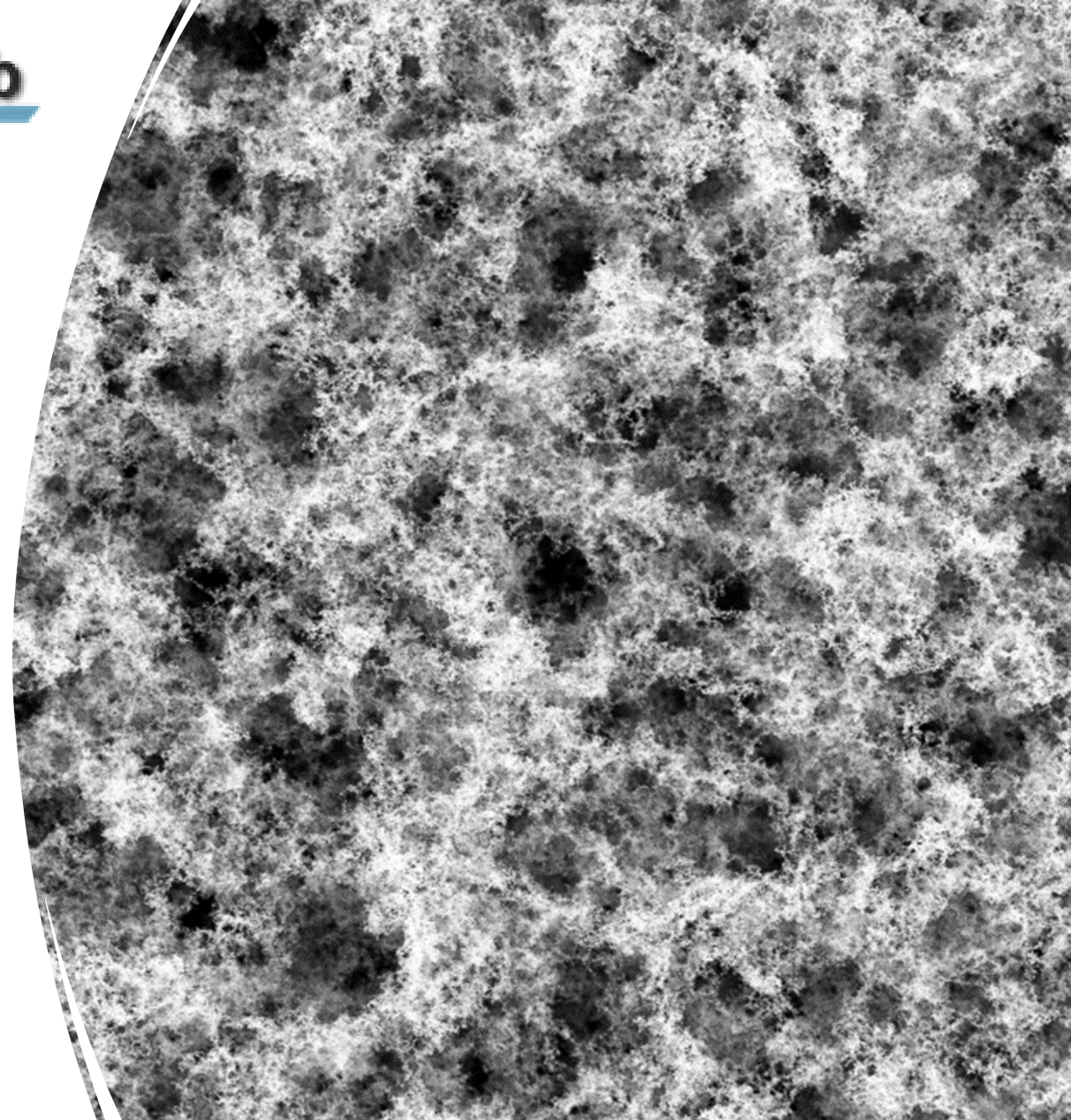


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 CUP D53D23002840006





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CUP D53D23002840006

**Thank you for
your attention!**