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

A. Maffini[1], D. Orecchia[1], A. Milani[1], M. Passoni[1], D. P. Molloy [2,3], G. Nersisyan[2],V Kantarelou[4], L. Giuffrida[4], D. Margarone [2,4]

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QUEEN'S UNIVERSITY BELFAST
HB11 ENERGY
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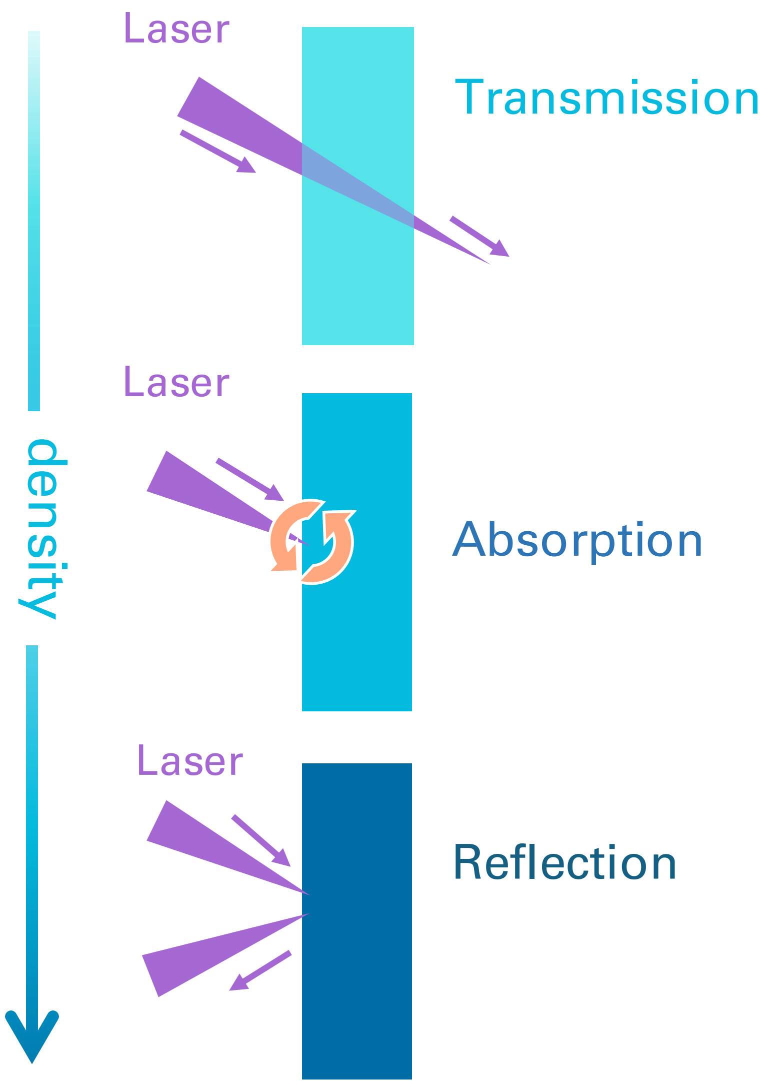
Synthesis, characterization and testing of hydrogenated boron nanofoams for laser-driven proton-boron fusion

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

Why Nanofoams?



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

M. Passoni et al., Plasma *Phys. Control. Fusion* **61,** (2020)
L. Fedeli et al., *Scientific reports* **8.1**, (2018)

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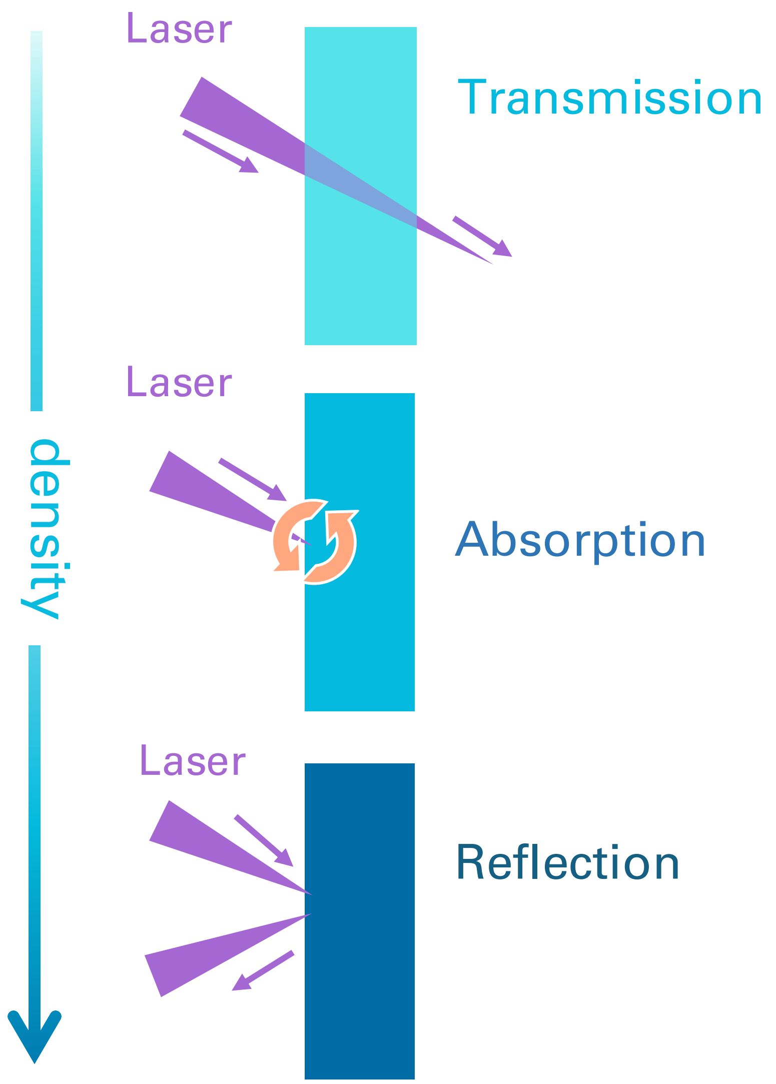

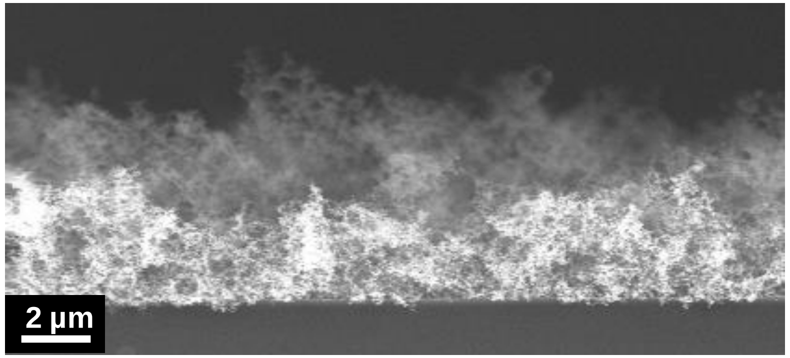

Nanostructured materials

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

Volumetric
interaction

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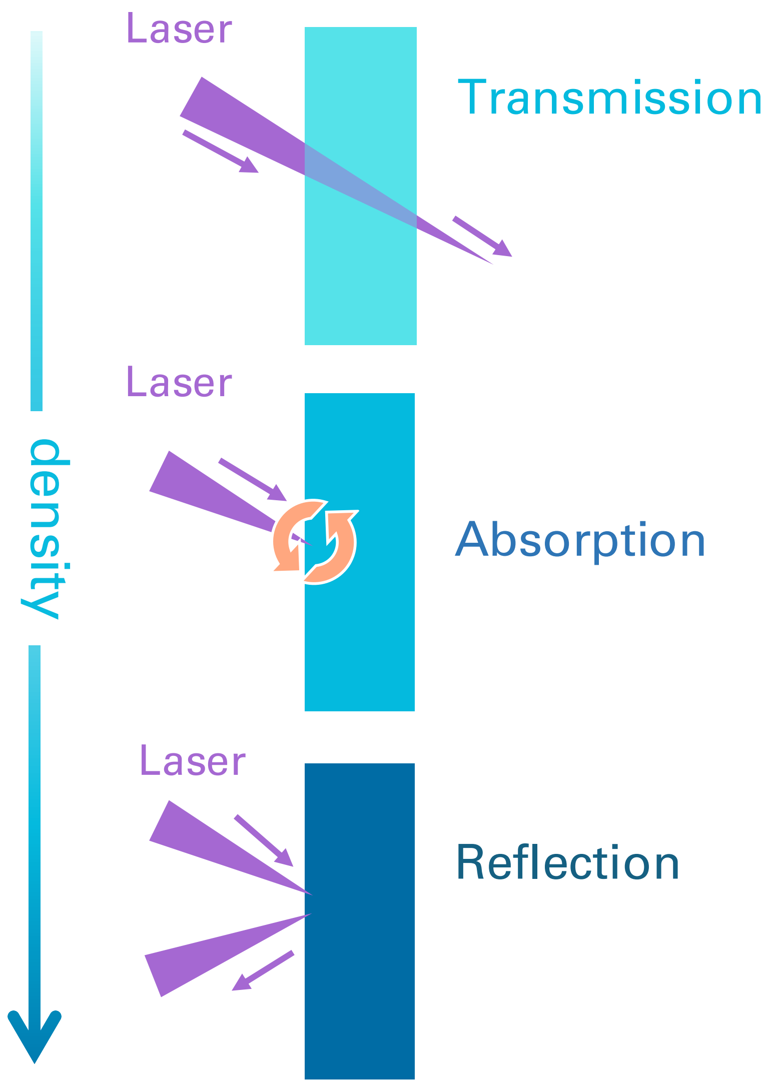

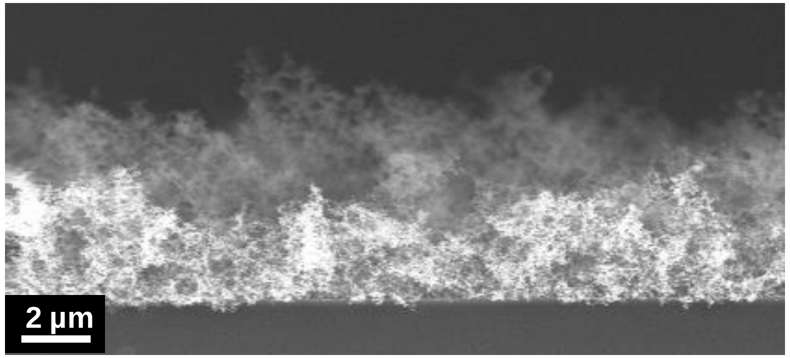

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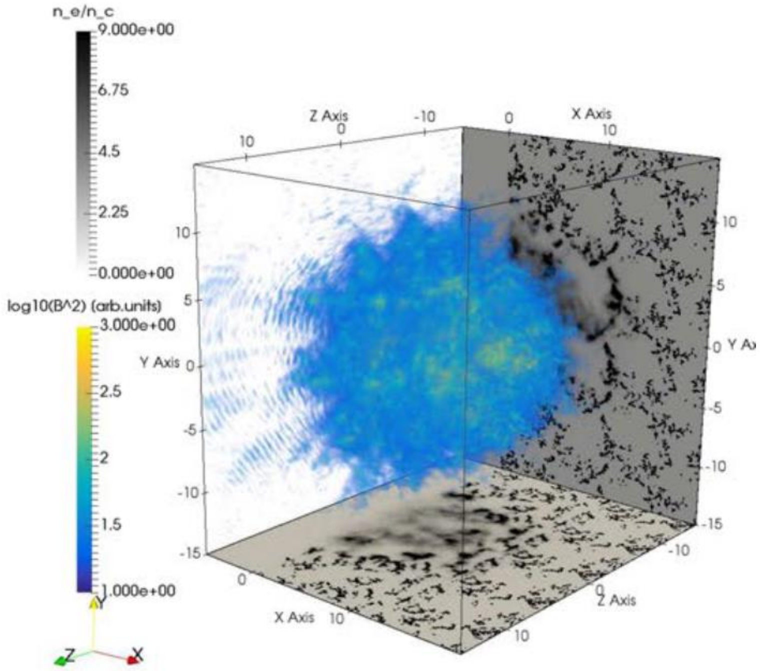


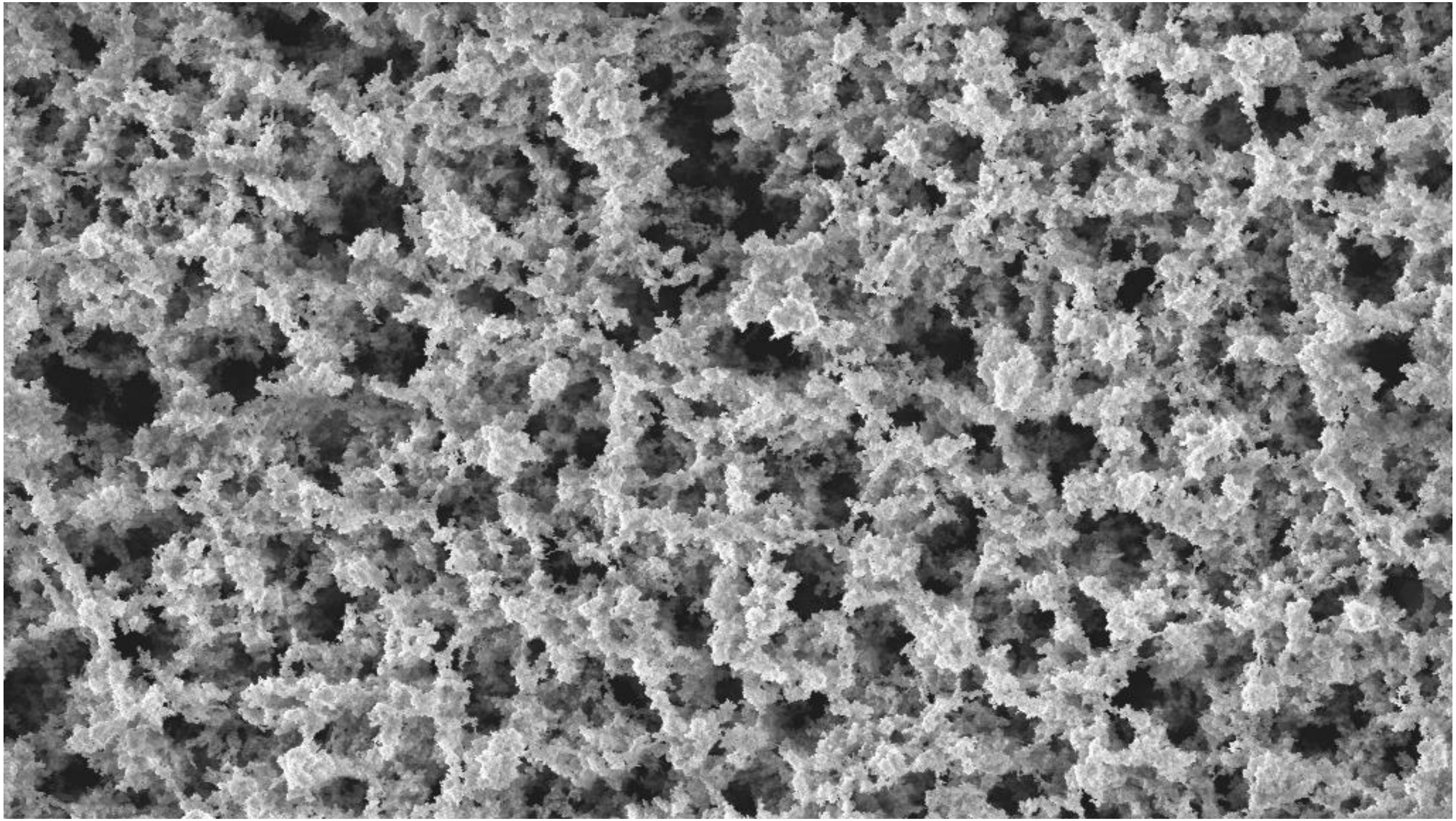
Volumetric interaction

Nanostructure **enhancement**

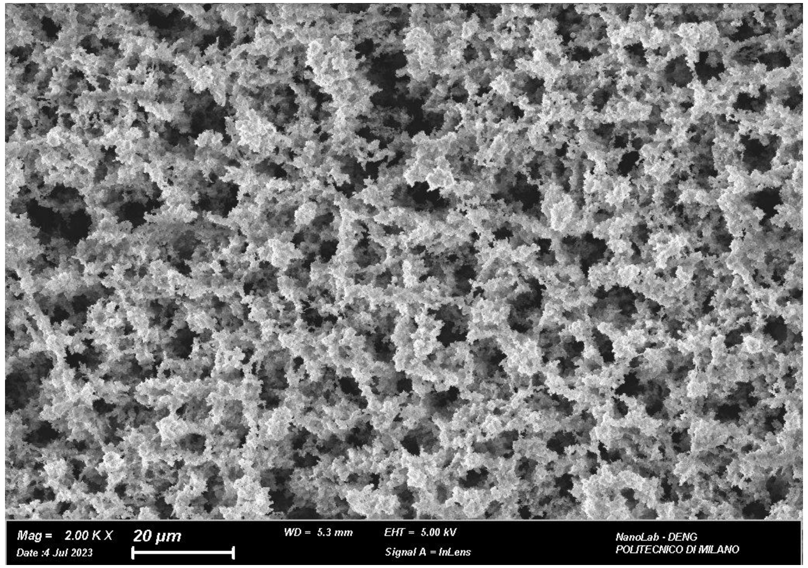
➢ **Efficient** laser absorption

M. Passoni et al., Plasma *Phys. Control. Fusion* **61,** (2020)
L. Fedeli et al., *Scientific reports* **8.1**, (2018)

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

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

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

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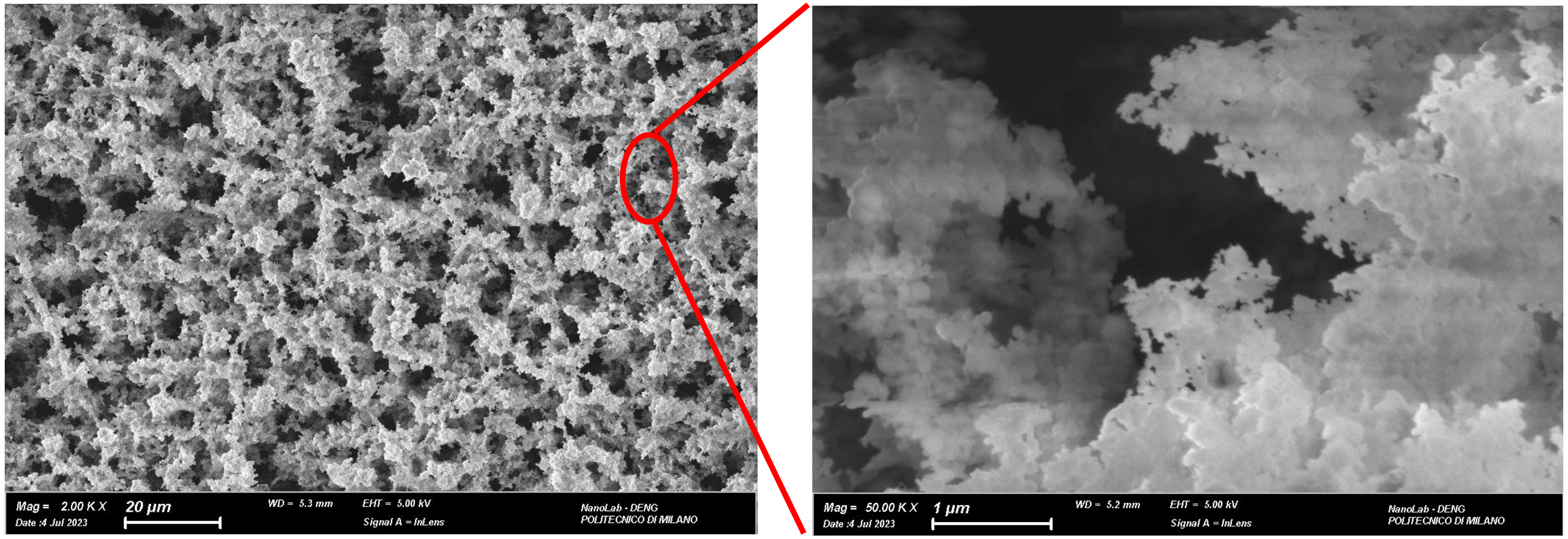

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Thickness: 1 to 100s µm

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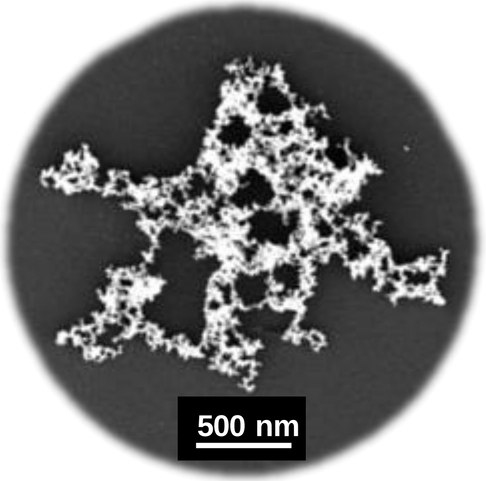
Fractal-like aggregates



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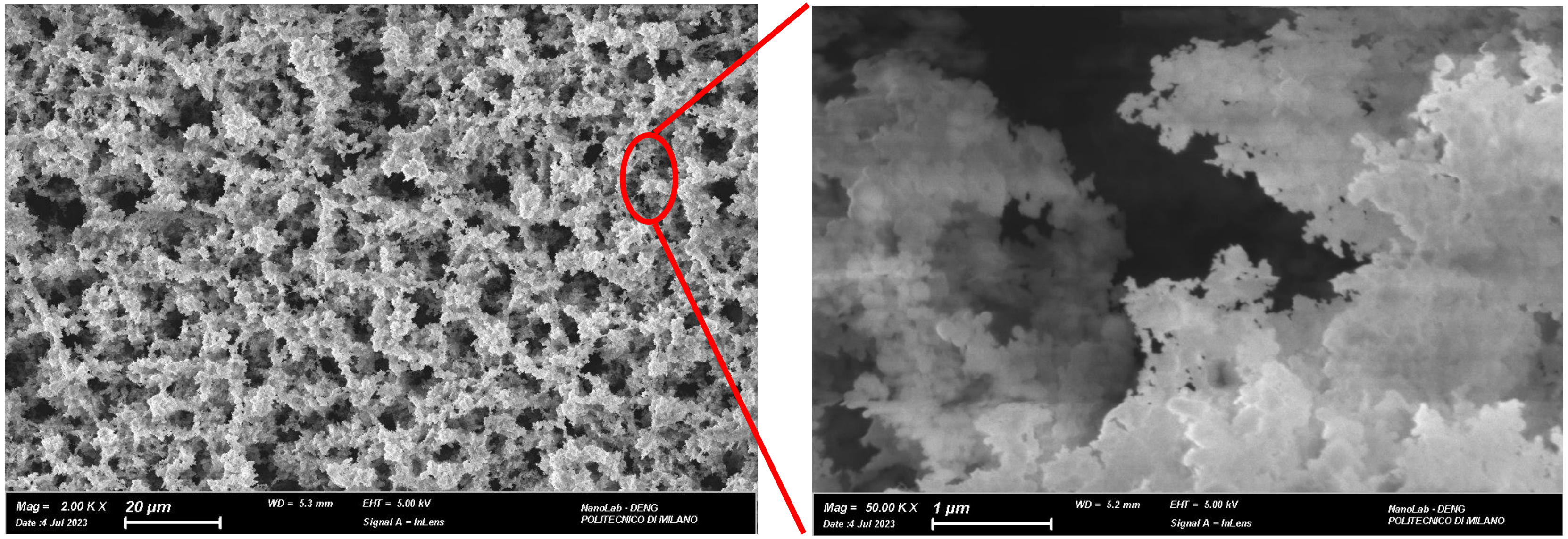

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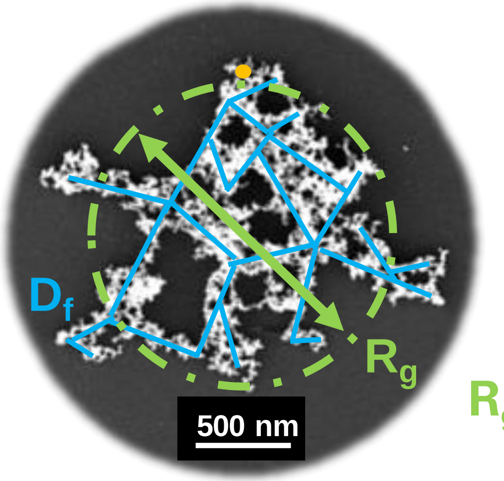

D_f Fractal dimension: ~ 1.8 – 2.2

R_g Gyration radius: 0.1 μm – 5 μm

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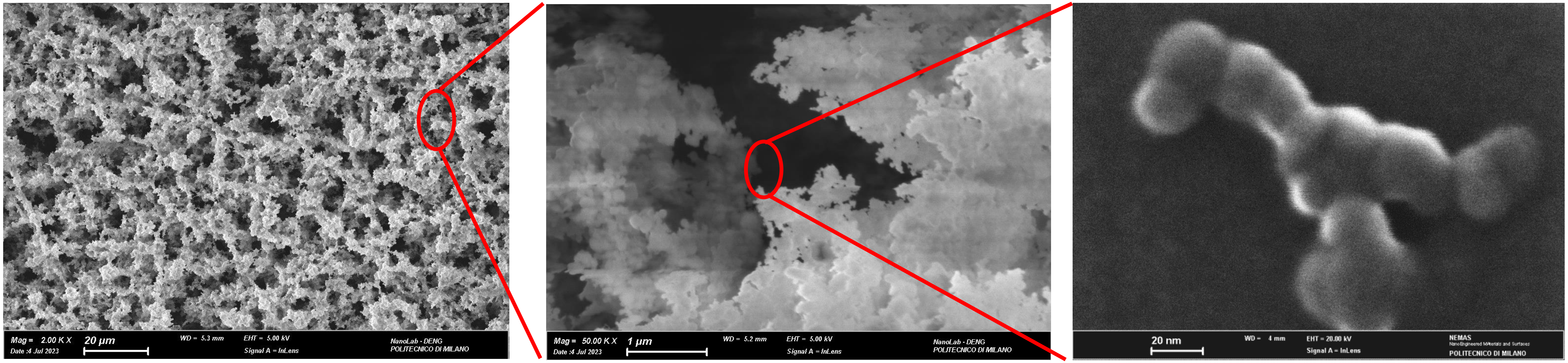

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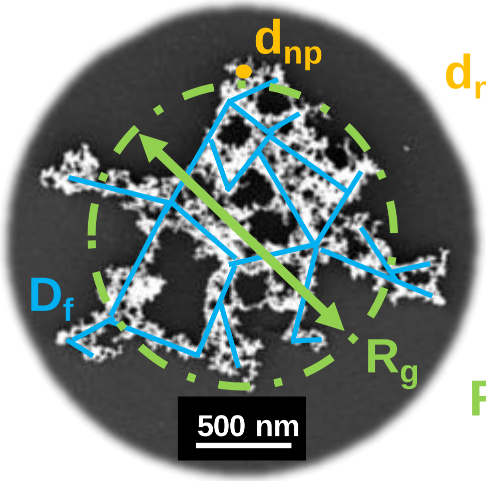

Nanoparticle constituents

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

D_f Fractal dimension: ~ 1.8 – 2.2

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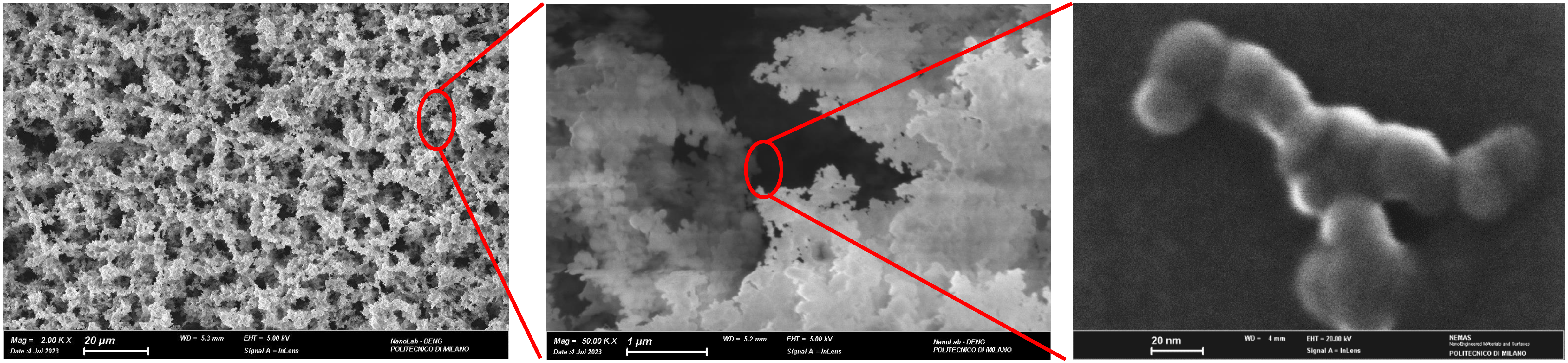


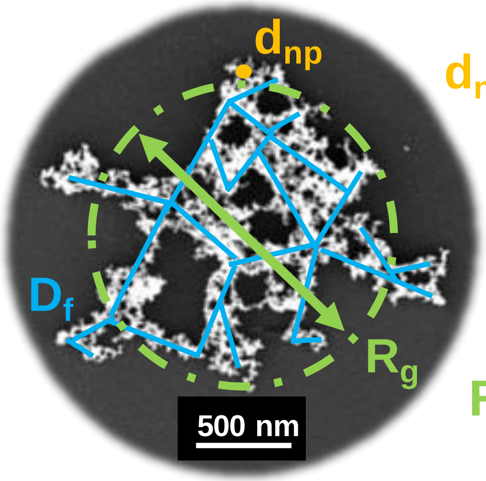
Multi-scale structure

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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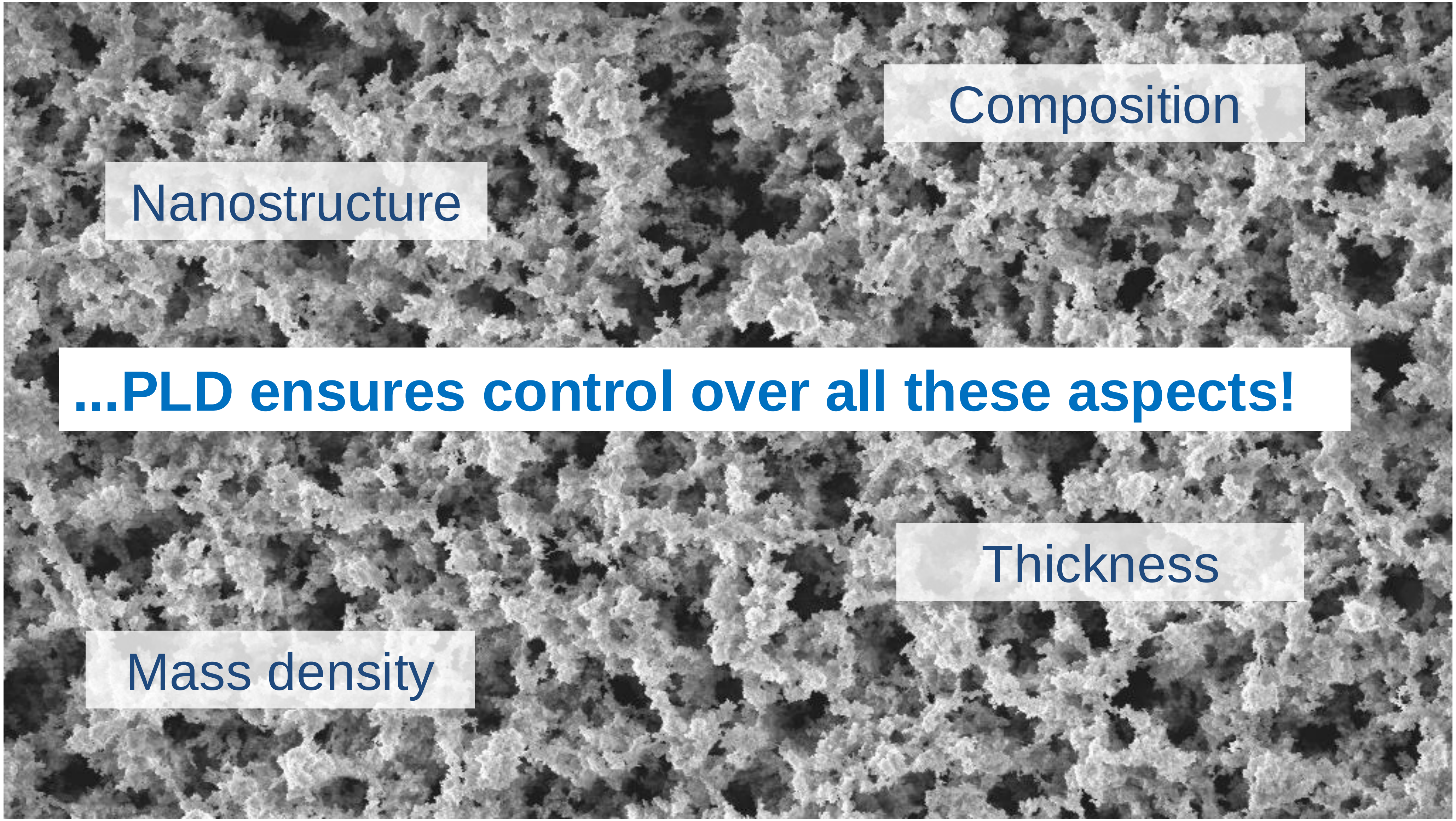
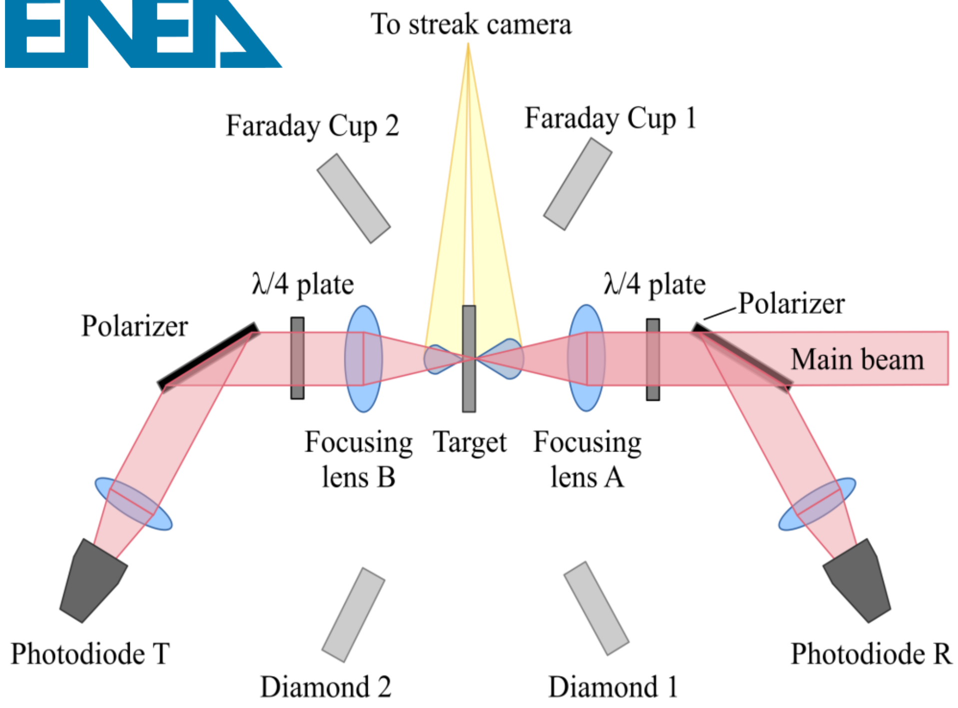
Why Pulsed Laser Deposited Nanofoams?



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

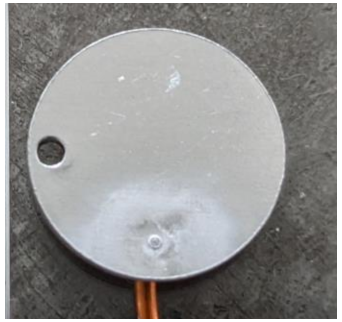
Nanofoams as ICF ablators

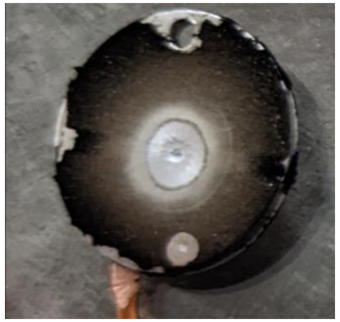


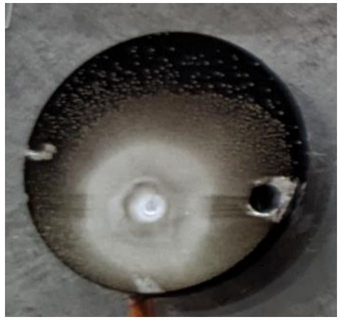
Wavelength = 1054 nm
Temporal FWHM = 3 ns
Intensity = 10^{14} W/cm^2
Ep = 40 J

See M. Cipriani's talk this morning!

No foam **Fractal-like** **Tree-like**

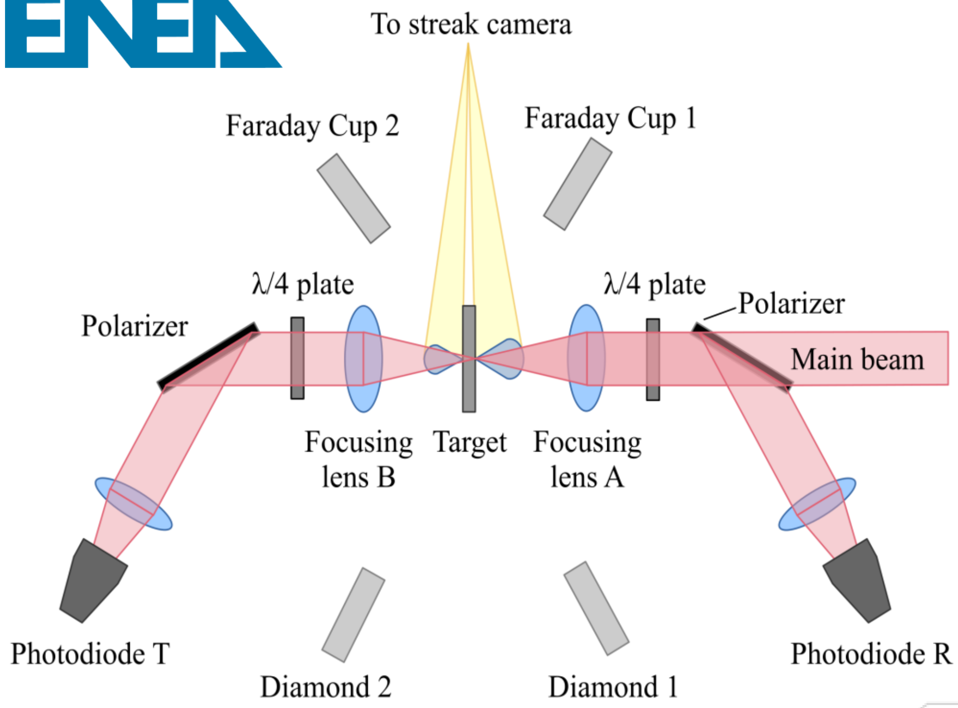






A. Maffini et al., Laser Part. Beams, 1214430, 1-9 (2023)
M. Cipriani et al., in preparation (2024)

Nanofoams as ICF ablators



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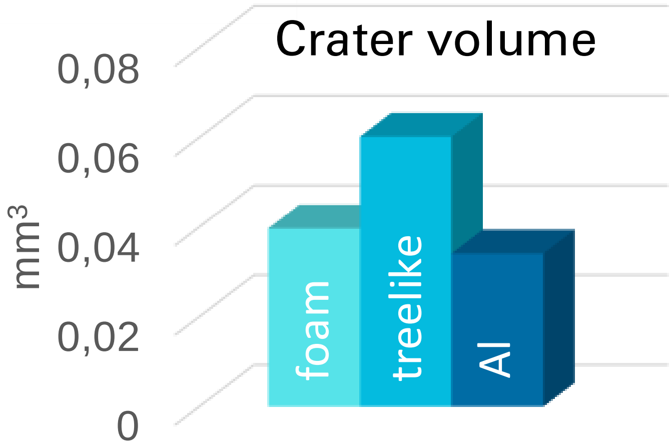

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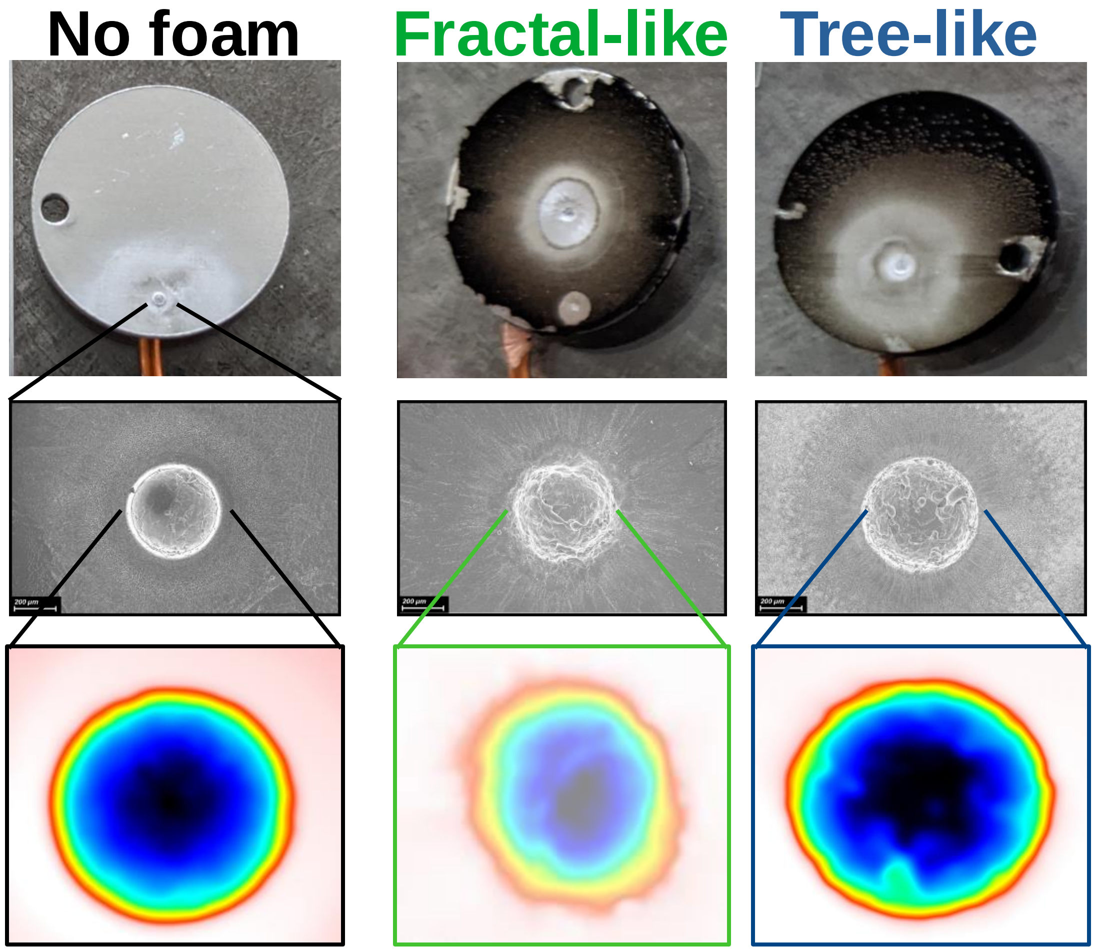
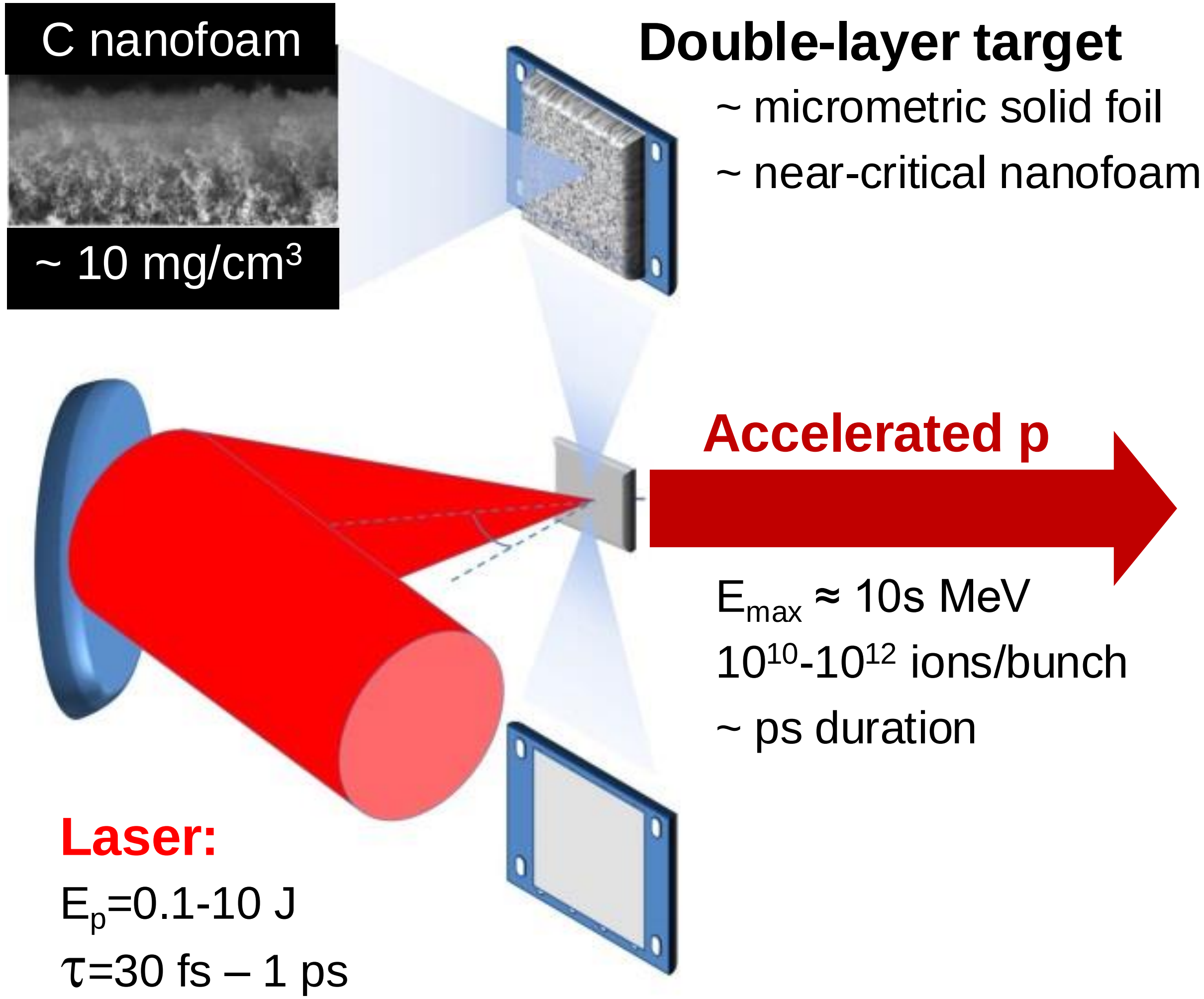


V ~ 3 * 10^7 μm^3 | V ~ 4* 10^7 μm^3 | **V ~ 6* 10^7 μm^3**

A. Maffini et al., Laser Part. Beams, 1214430, 1-9 (2023)
M. Cipriani et al., in preparation (2024)

Nanofoams for advanced TNSA



Double-layer target

~ micrometric solid foil

~ near-critical nanofoam

Accelerated p

$E_{max} \approx$ 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

M. Passoni et al., Plasma *Phys. Control. Fusion* **61,** (2020)
I. Prencipe et al., *New Jour. Physics* **23.9** (2021)

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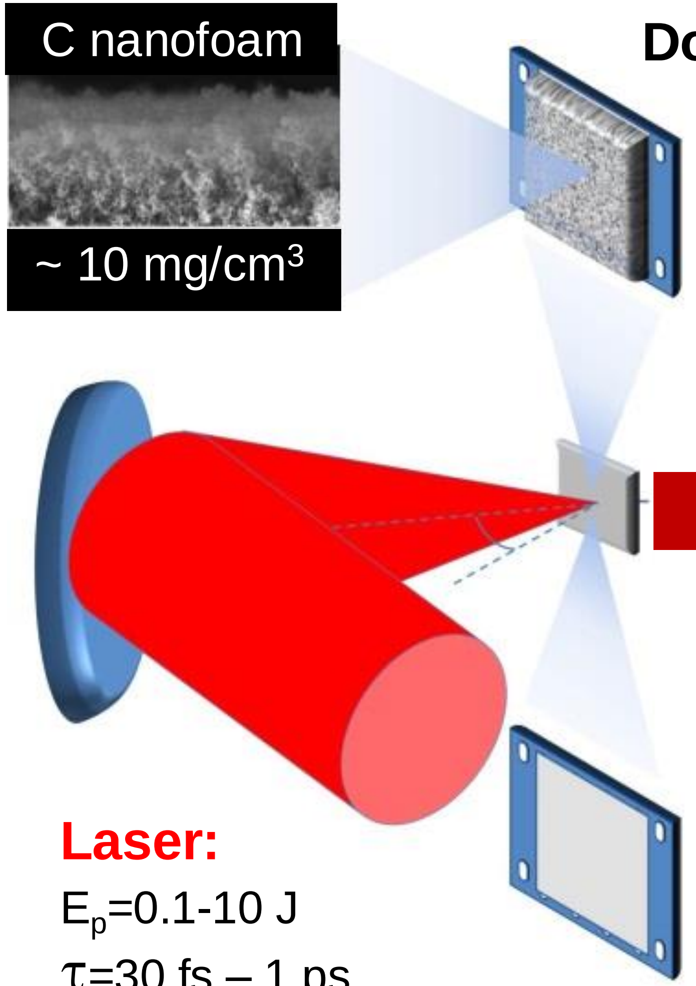


Double-layer target

- ~ micrometric solid foil
- ~ near-critical nanofoam

Accelerated p

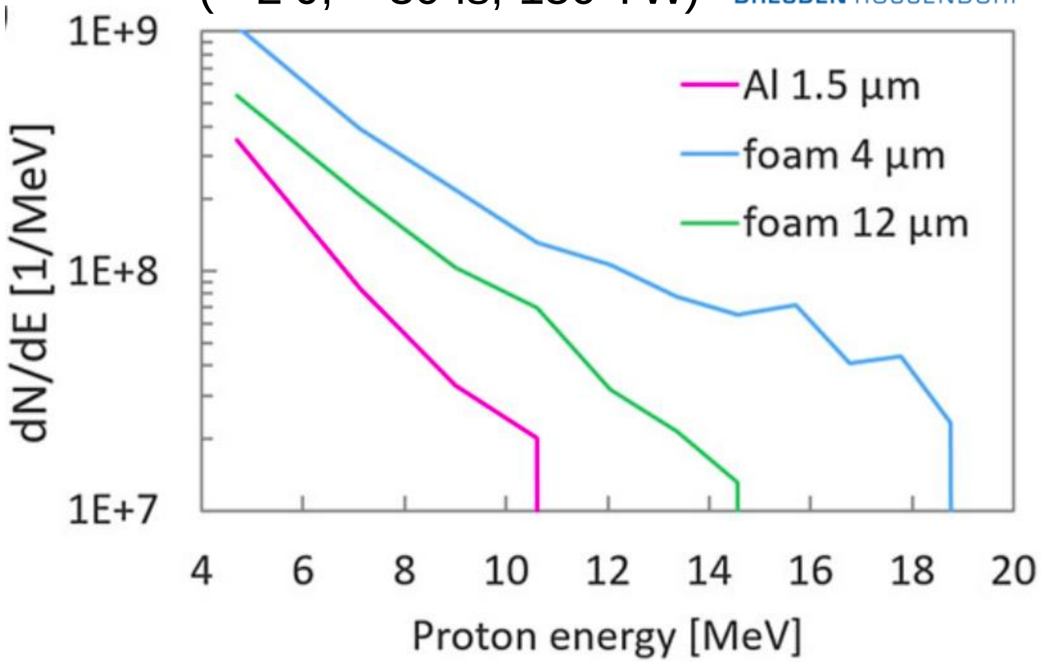
E_{max} ≈ 10s MeV
10^{10}-10^{12} ions/bunch
~ ps duration

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!

M. Passoni et al., Plasma *Phys. Control. Fusion* **61,** (2020)
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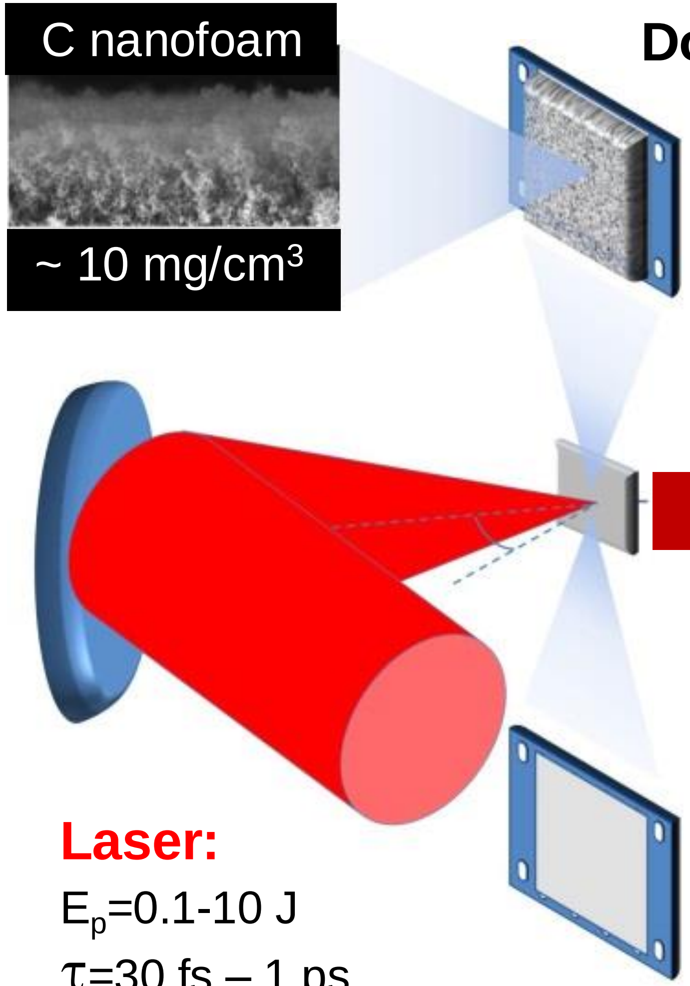
Nanofoams for advanced TNSA



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HZDR
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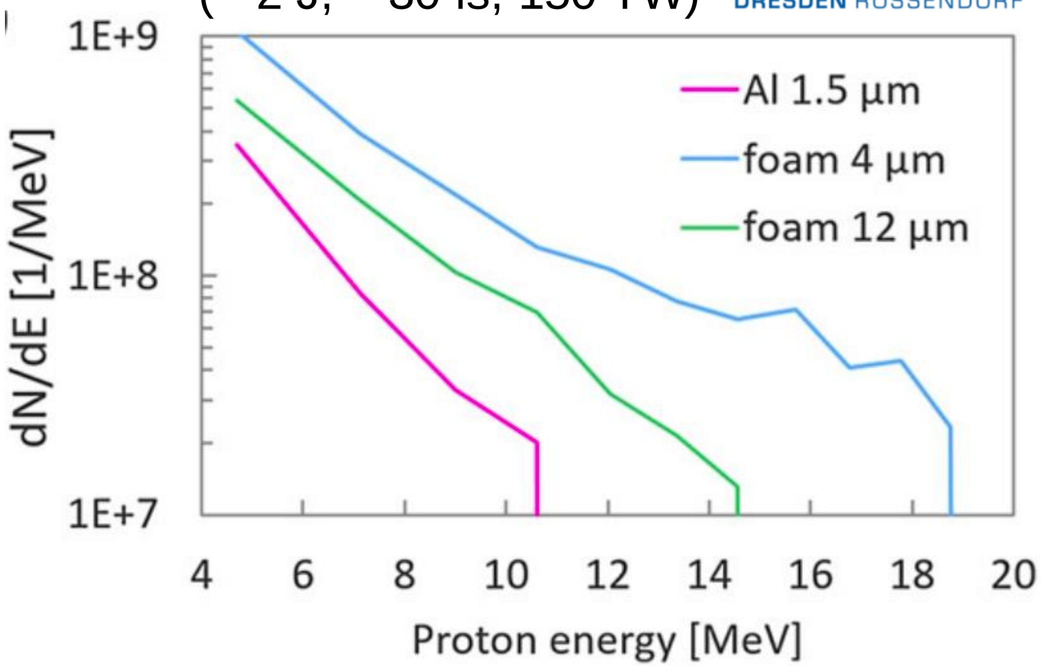
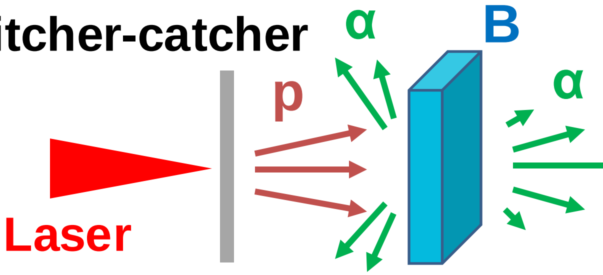


Pitcher-catcher



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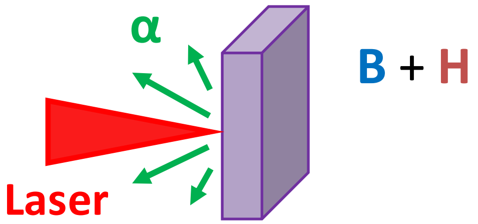
Nanofoams for in-target p-11B fusion

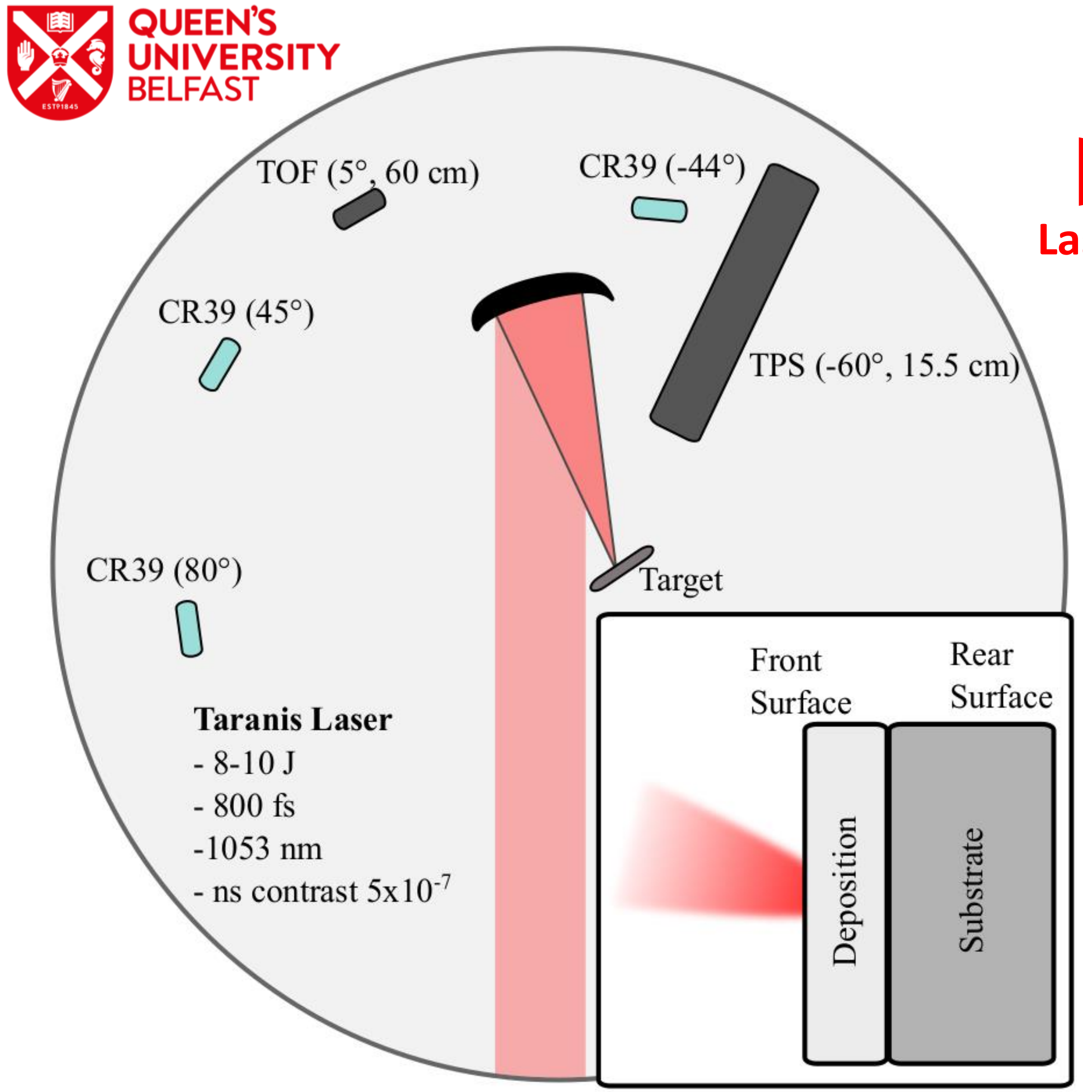
In-target



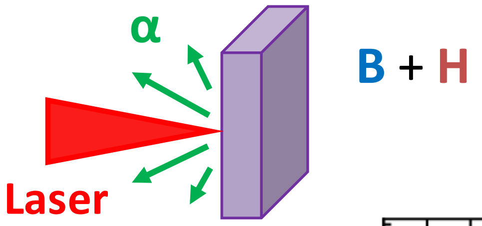
See D. Molloy's talk this morning!

D. Molloy et al., submitted to *Physical Review Research* (2024)

Nanofoams for in-target p-11B fusion



In-target



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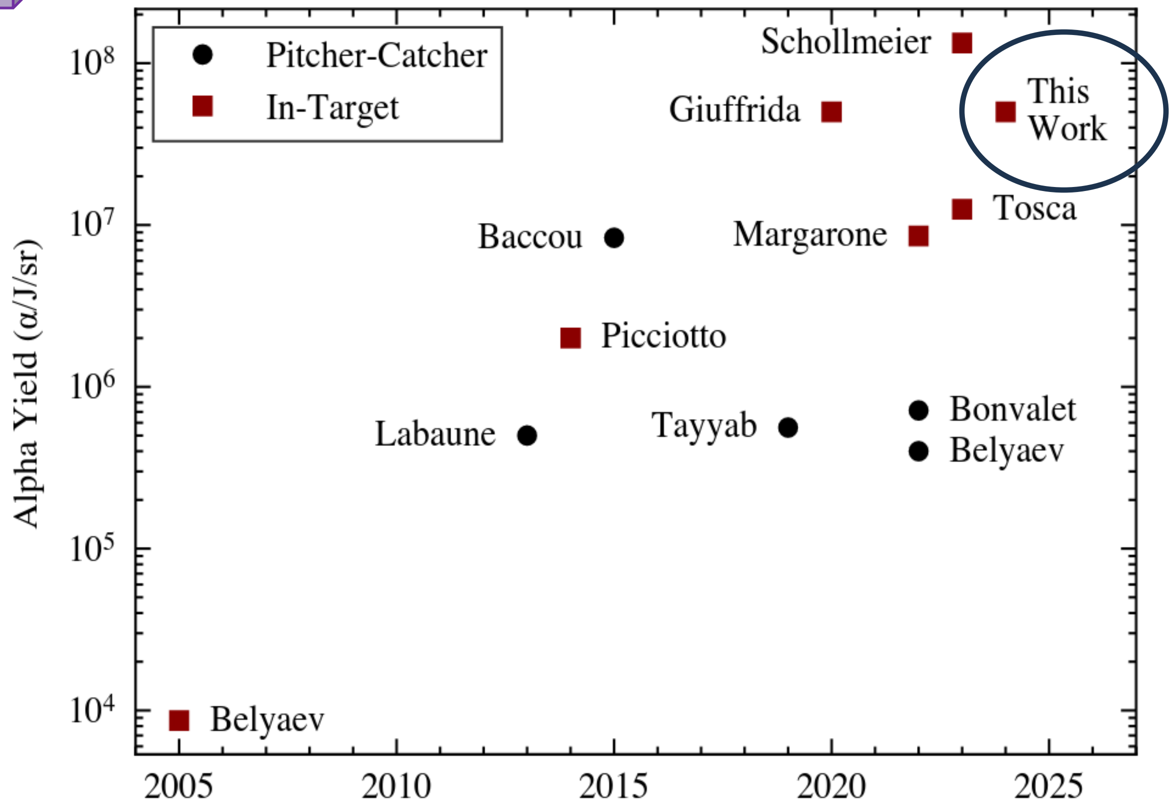

D. Molloy et al., submitted to *Physical Review Research* (2024)

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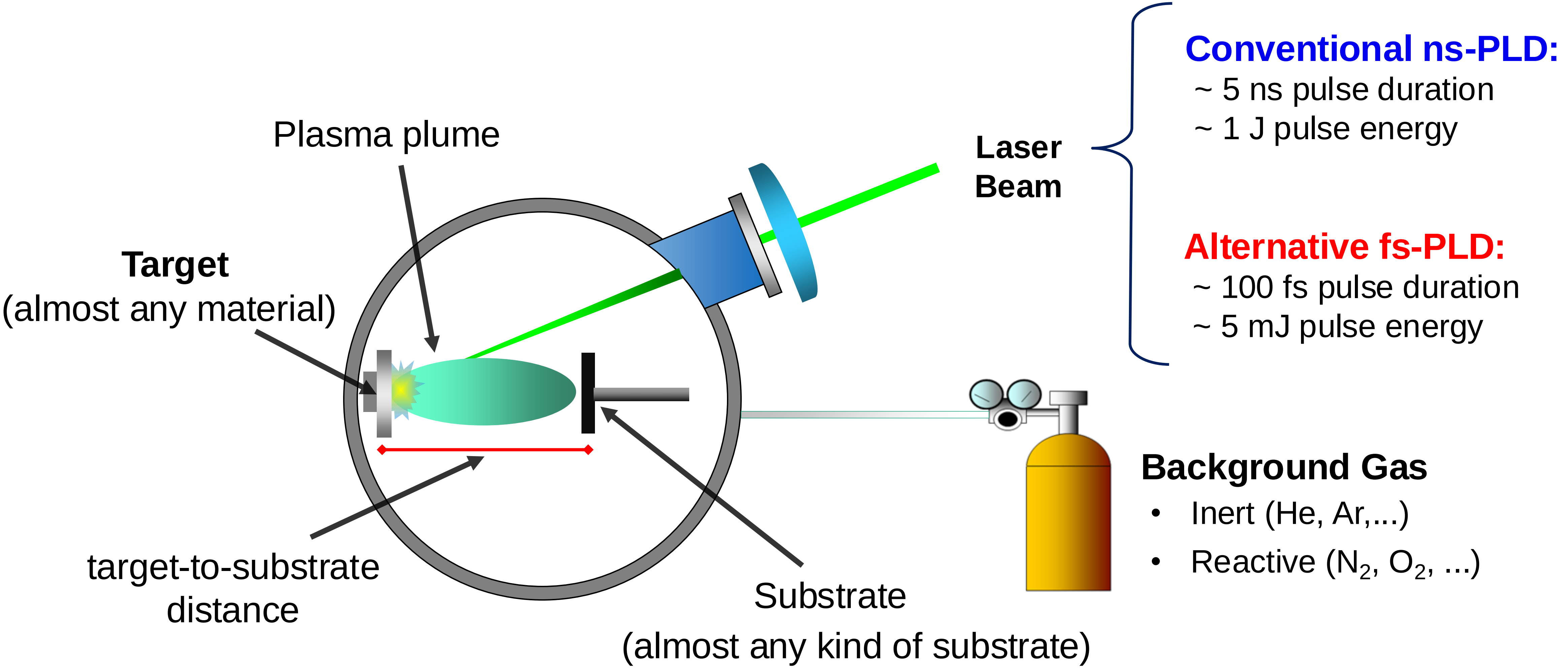
How does Pulsed Laser Deposition work?



NanoLab

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404
A. Maffini et al., *Applied Surface Science* **599** (2022) *153859*

Foam properties control

Nano-scale

- Crystalline structure & composition
- Nanoparticle size

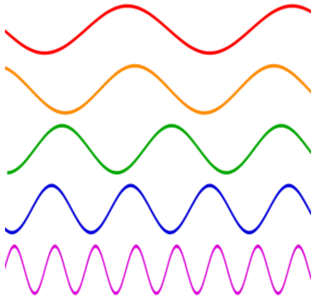
Micro-scale

- Aggregate size
- Morphology

Macro-scale

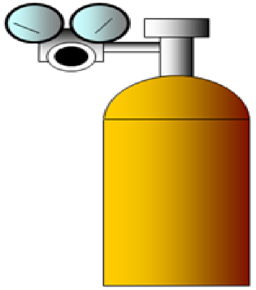
- Uniformity
- Thickness profile

Pulse Duration

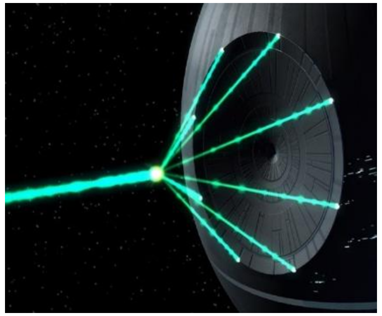


Target composition

Gas pressure



Laser Fluence



Deposition time

PLD process parameters

A. Maffini et al., *Physical Review Materials* **3** (2019) 083404
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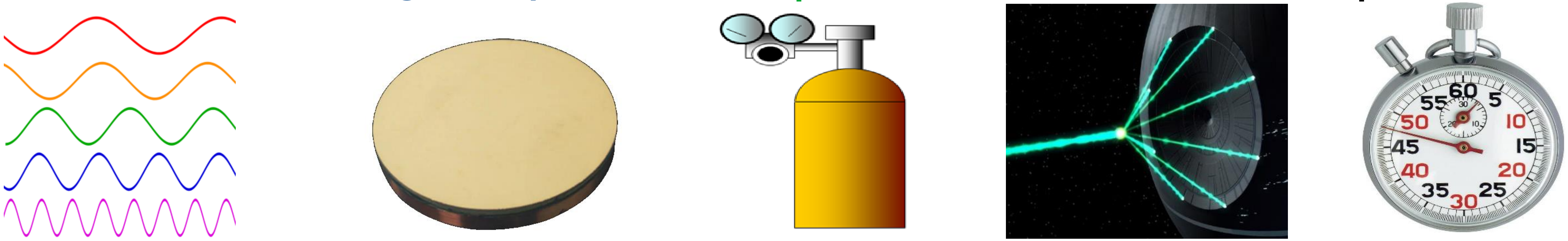
Pulse Duration **Target composition** **Gas pressure** **Laser Fluence** **Deposition time**



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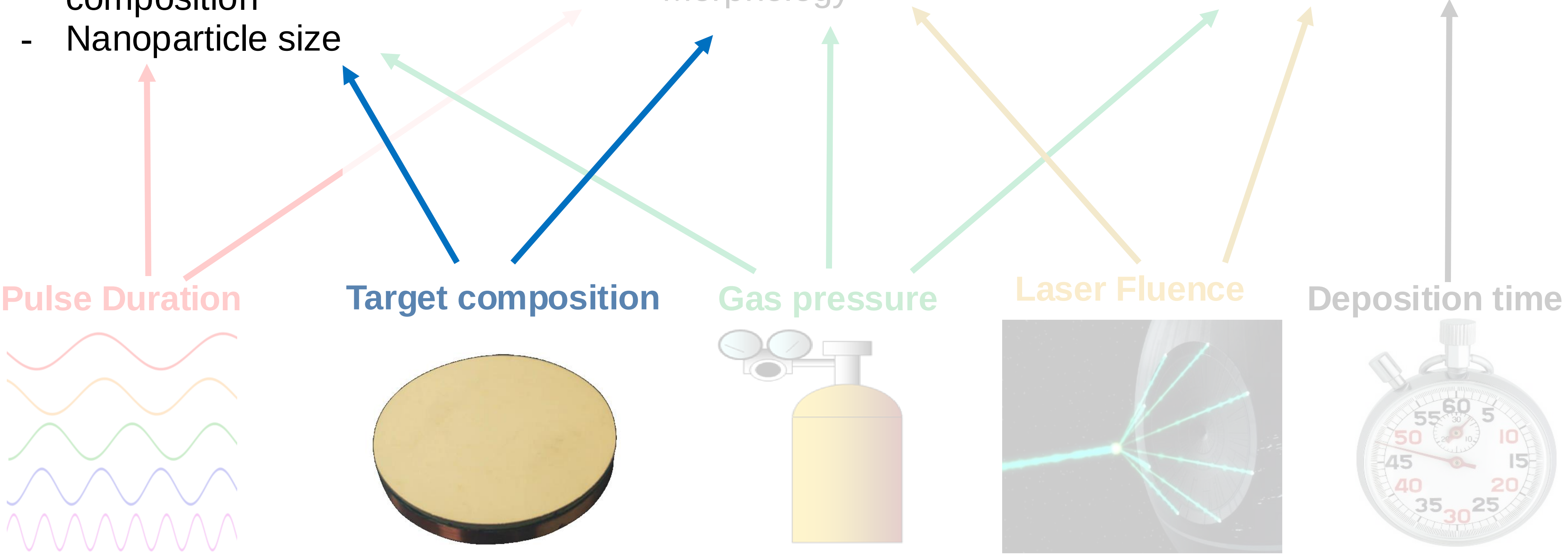
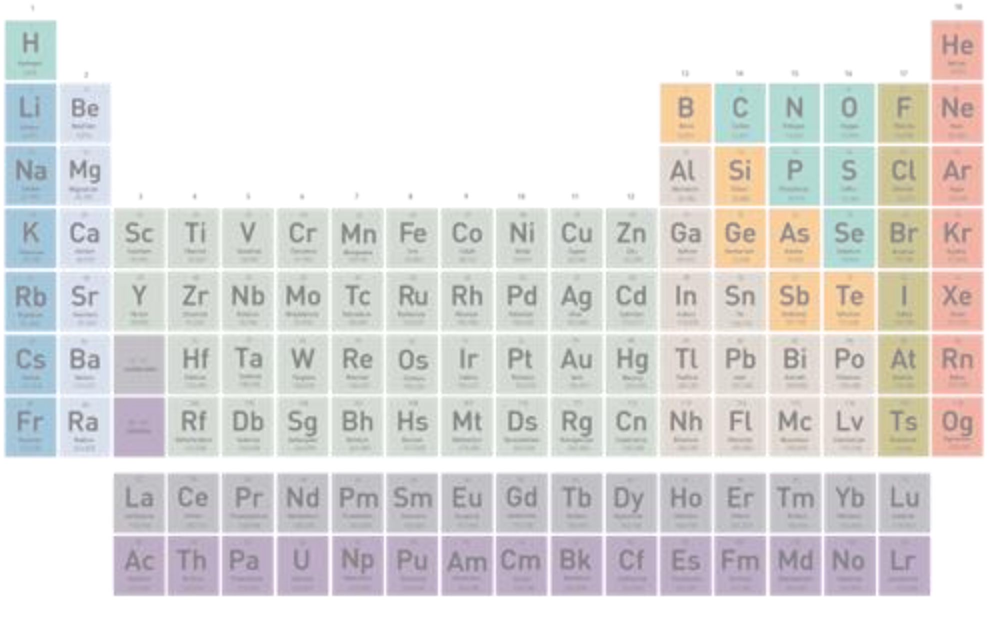


PLD process parameters

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

A lot of elements to play with...



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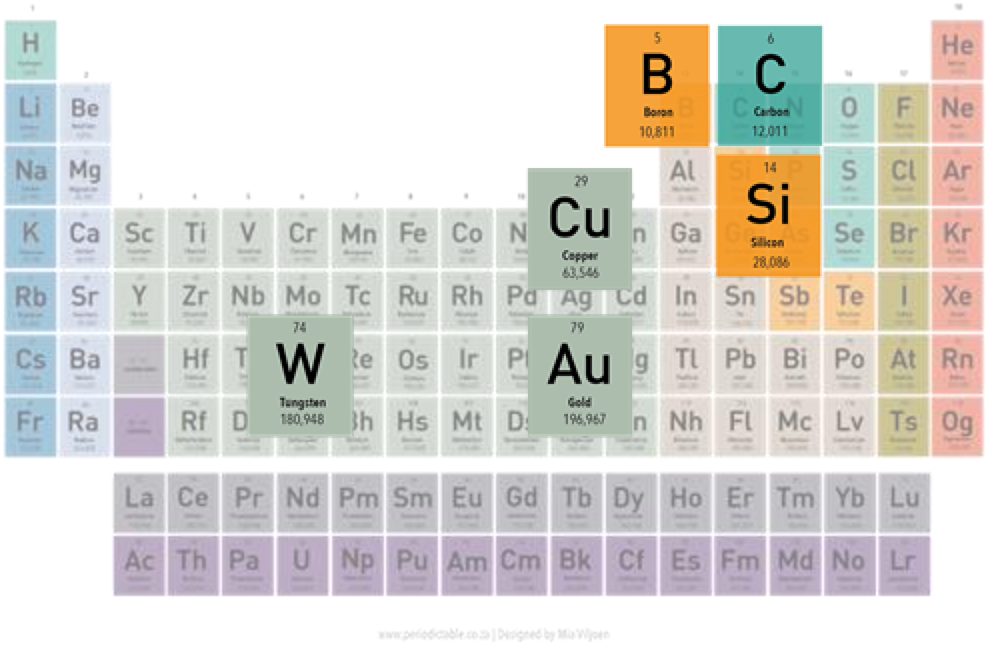
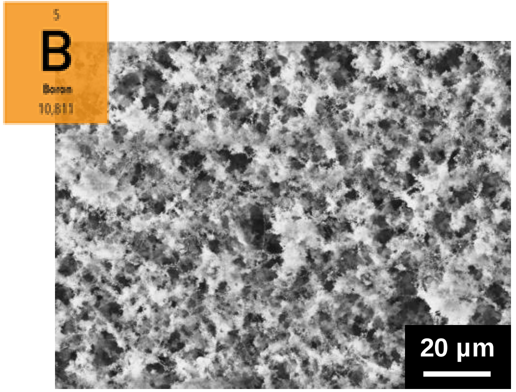
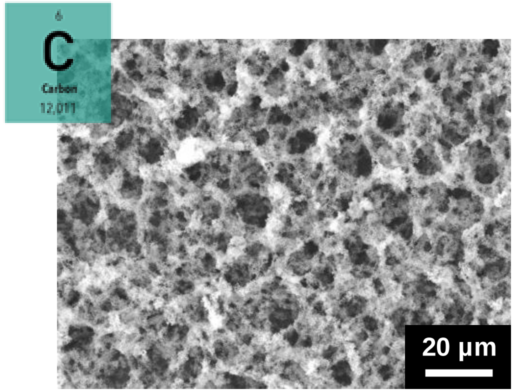


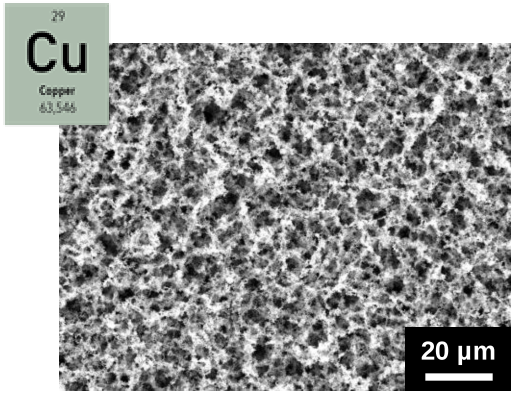
D. Orecchia et al., *Small Structures* **5**, 2024

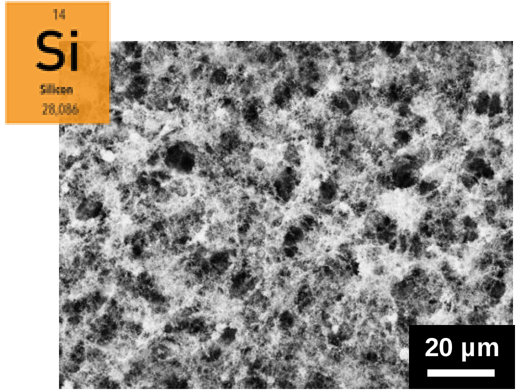
A lot of elements to play with...

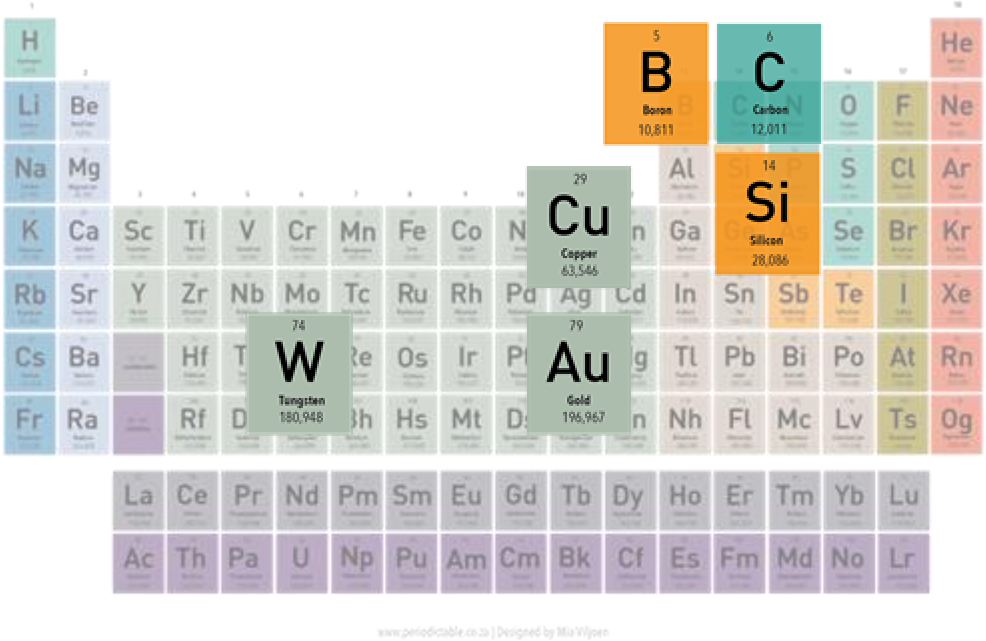
Deposition with fs-PLD:
- Same fluence, 0.1 J/cm^2
- Different pressure

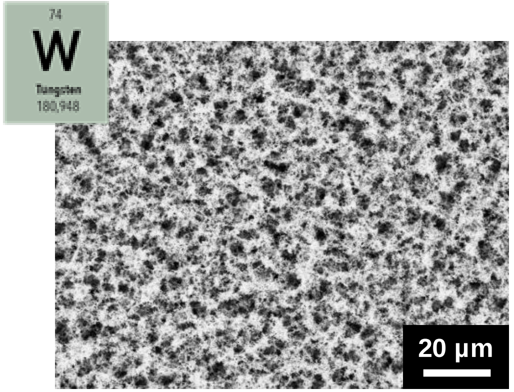


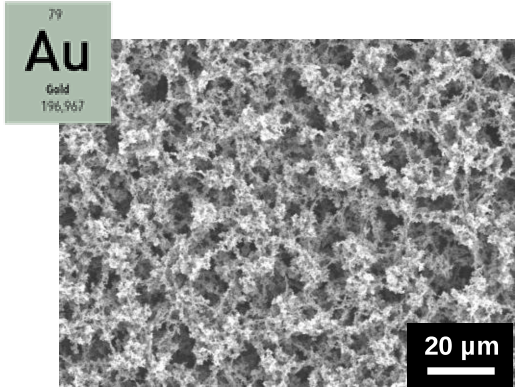












A lot of elements to play with...

Deposition with fs-PLD:
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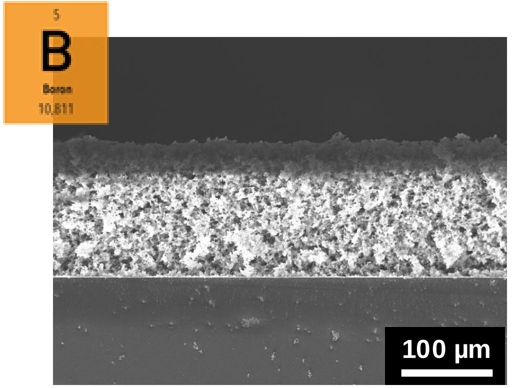
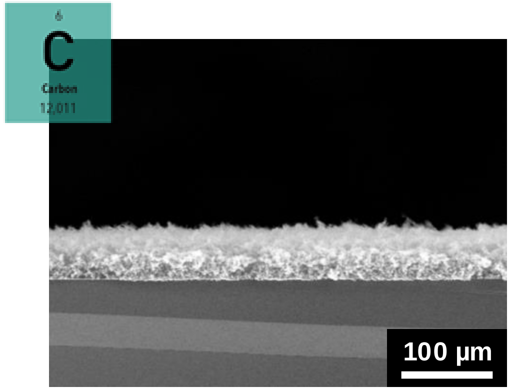
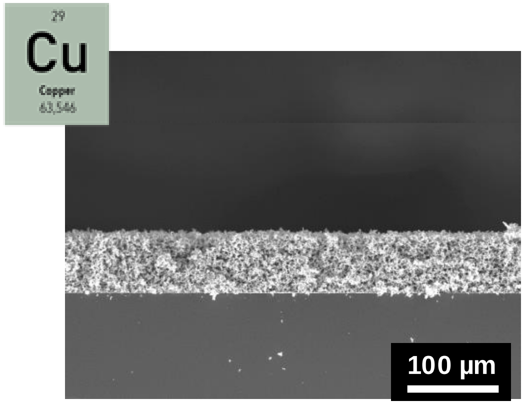
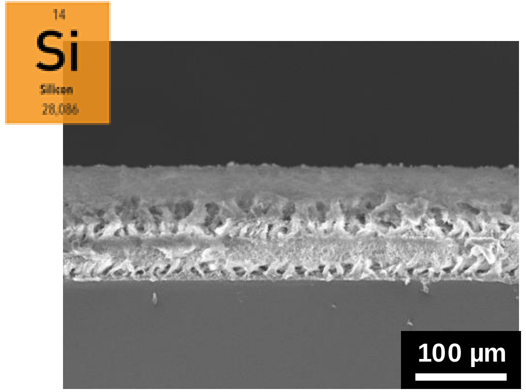
- Different pressure

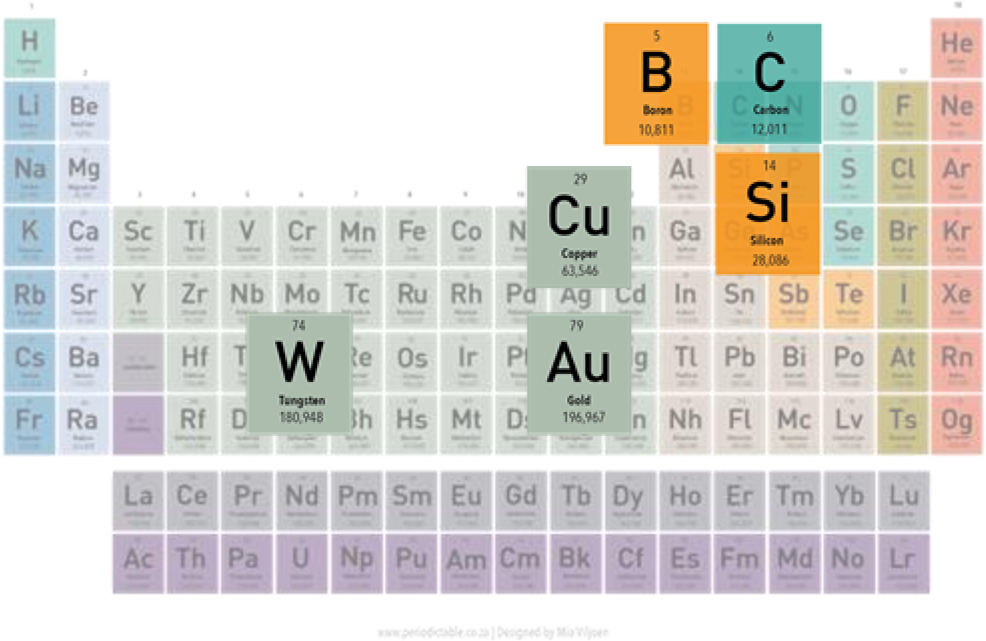
Thickness > 100 µm

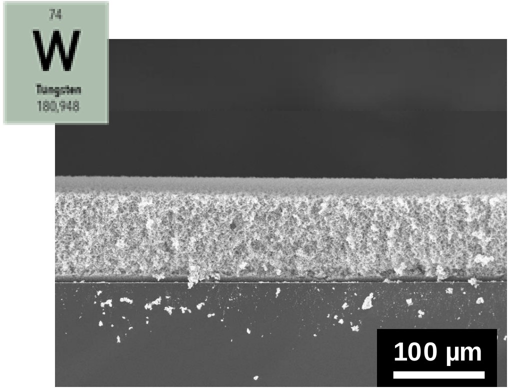


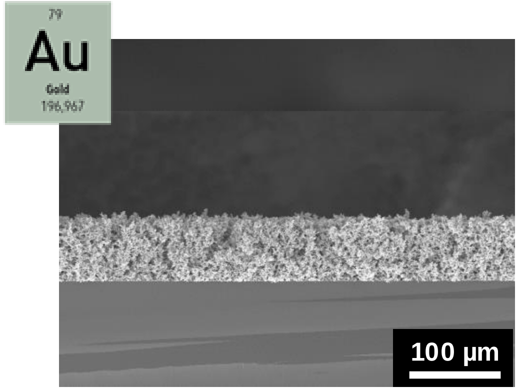






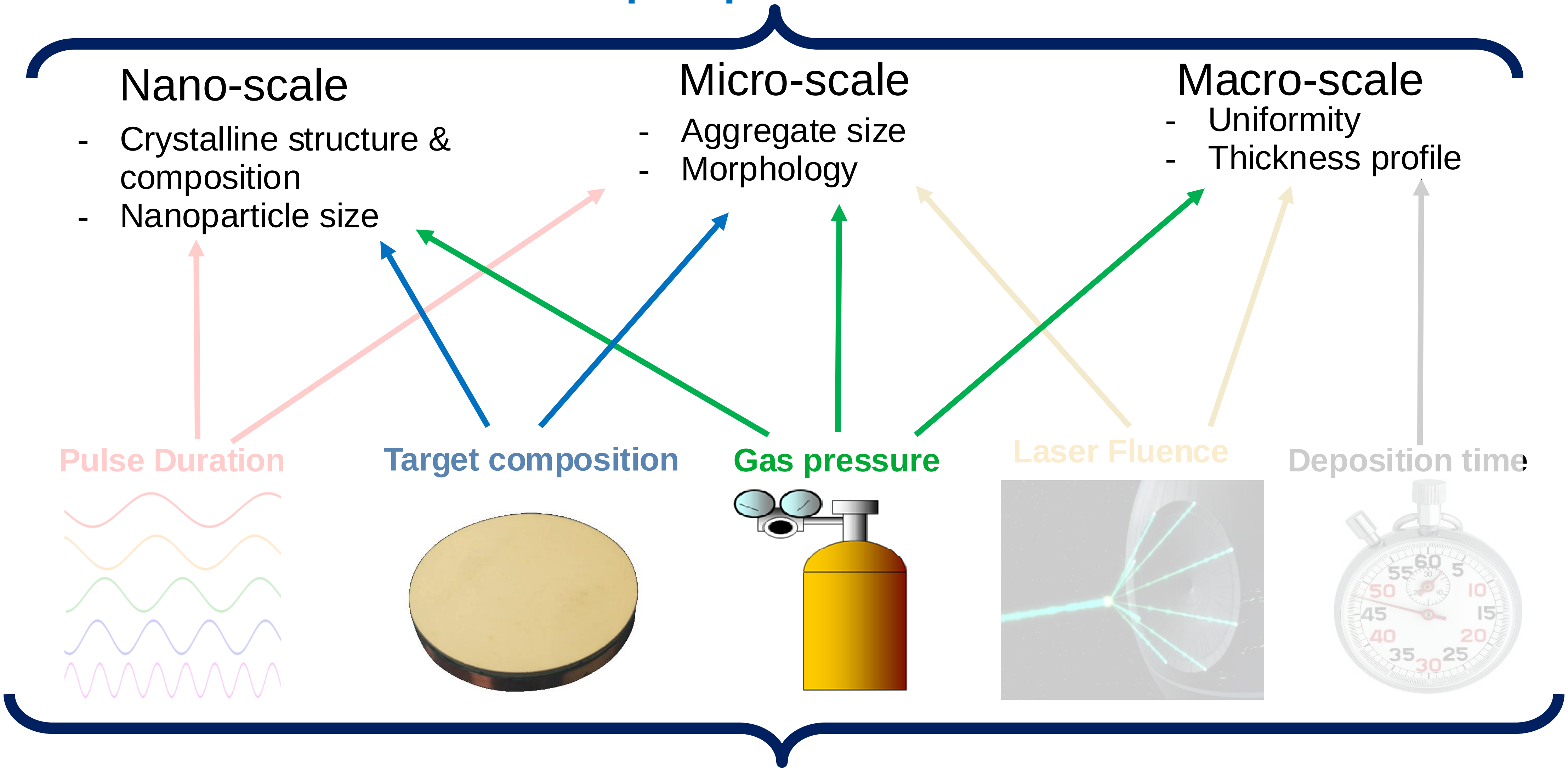






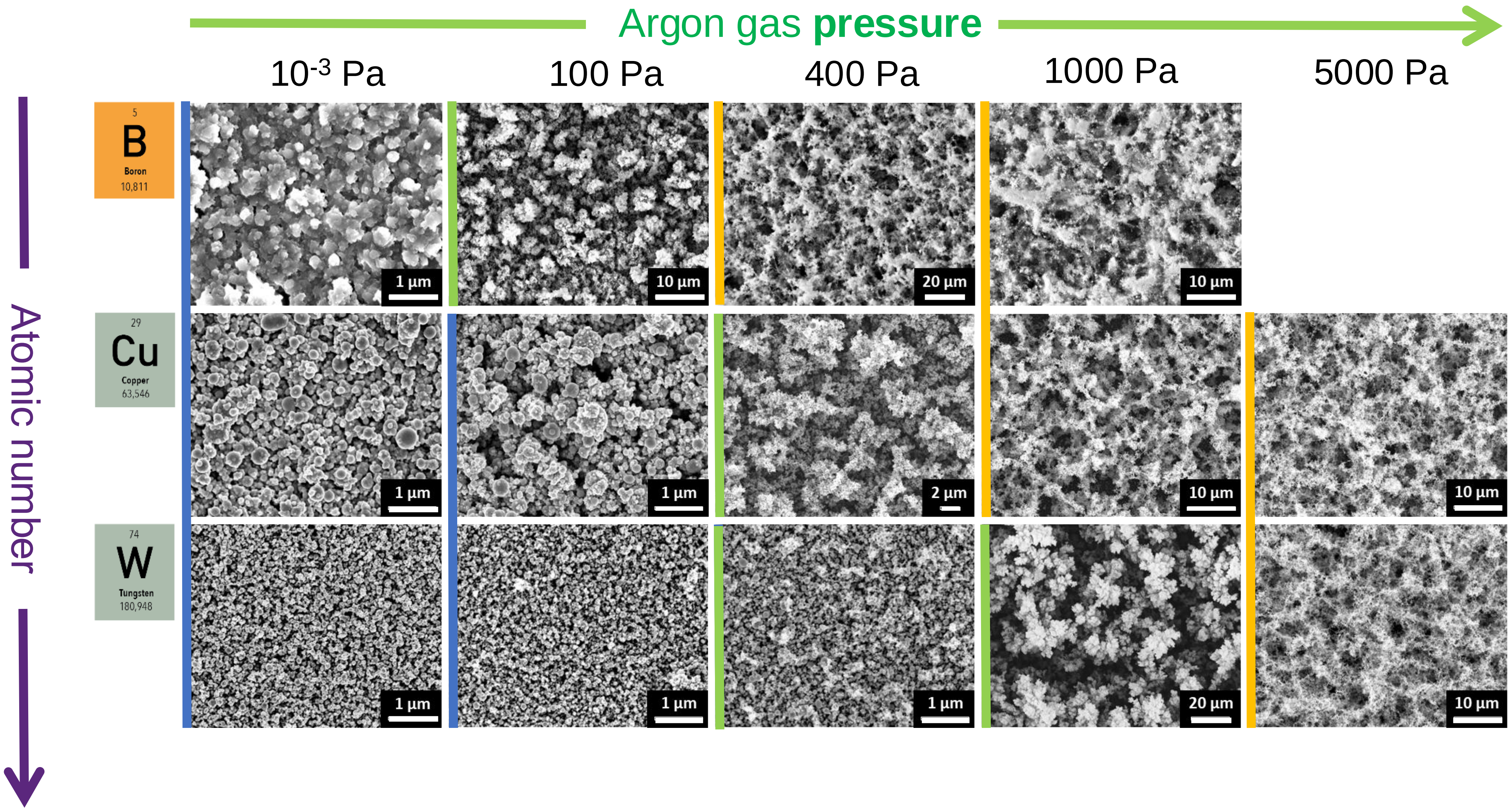
D. Orecchia et al., *Small Structures* **5**, 2024

Foam properties control



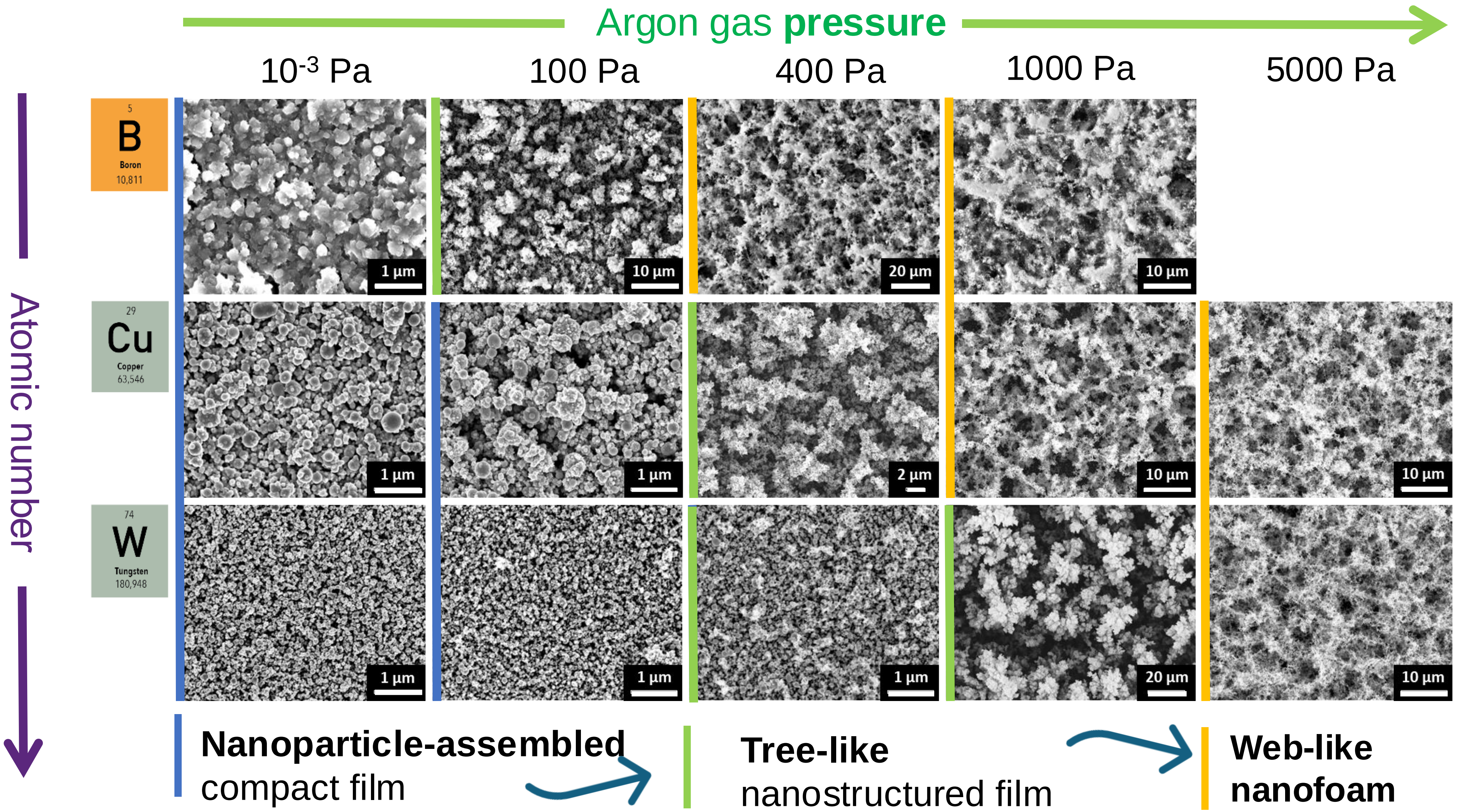
PLD process parameters

Fine tuning of nanofoam morphology



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

Fine tuning of nanofoam morphology



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

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

Nanofoam characterization

Integration of:

- Scanning Electron Microscopy

Information on:

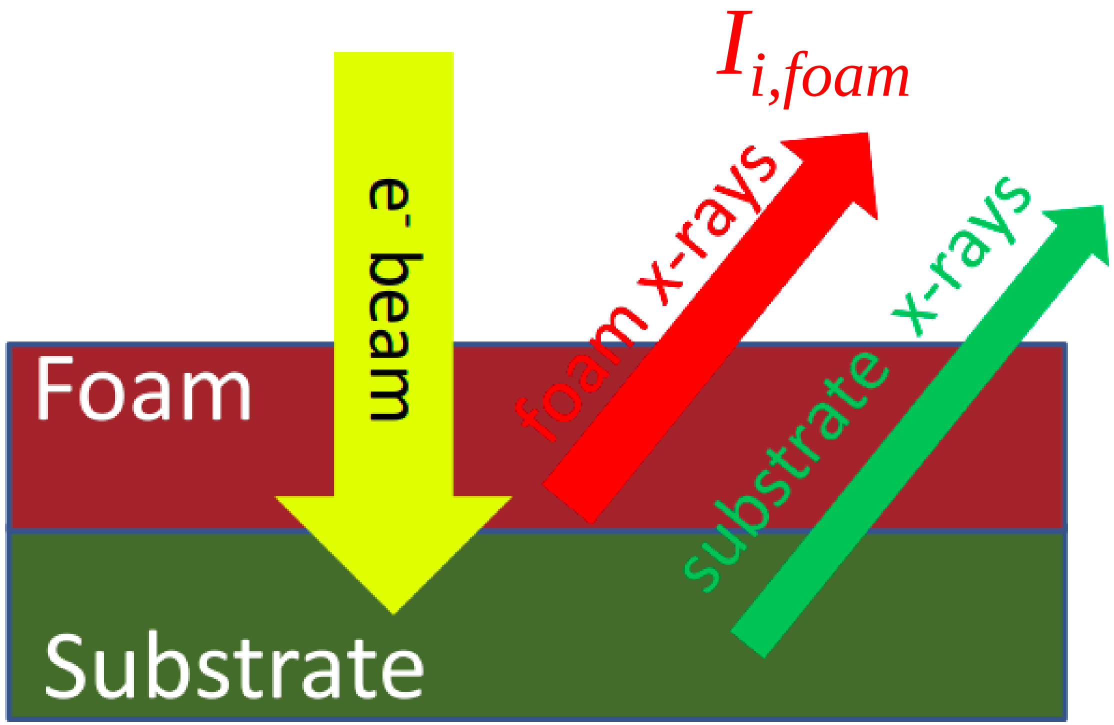
- Morphology
- Thickness *d*

A. Pazzaglia et al., *Material Characterization* **153**, 92 (2019)

Nanofoam characterization

Integration of:
- Scanning Electron Microscopy
- Energy Dispersive X-Ray Spectroscopy

Information on:
- Morphology
- Thickness d
- Composition c_i



A. Pazzaglia et al., *Material Characterization* **153**, 92 (2019)

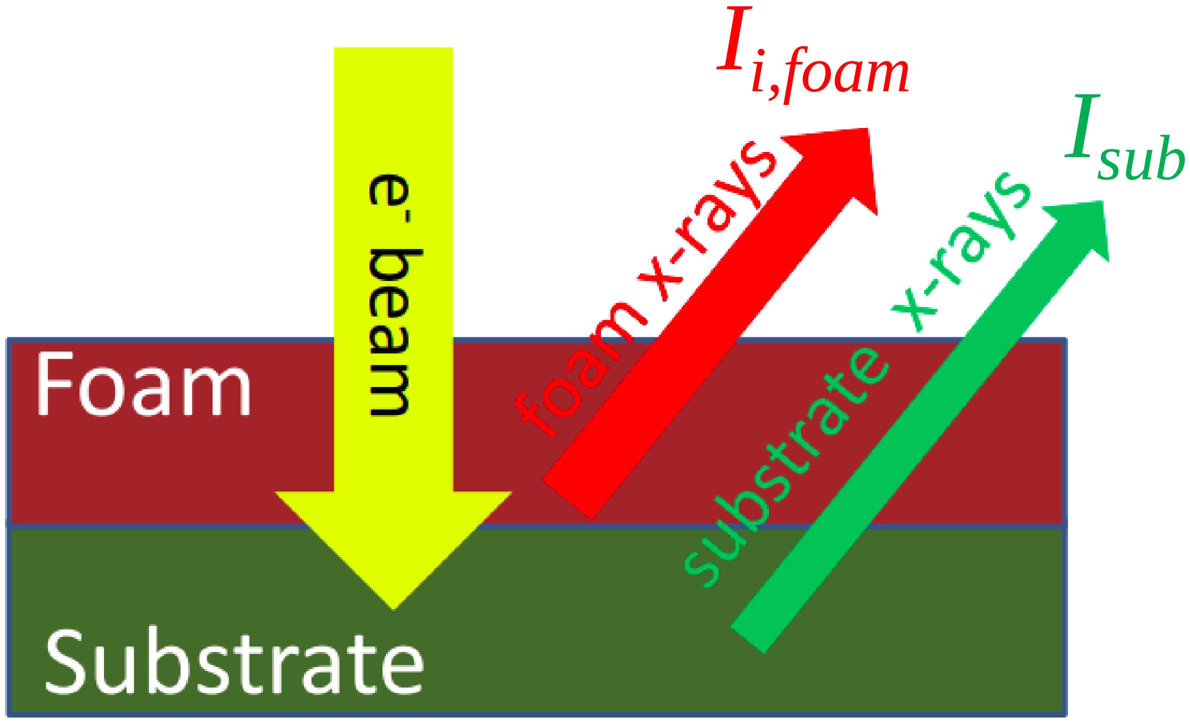
Nanofoam characterization

Integration of:

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

Information on:

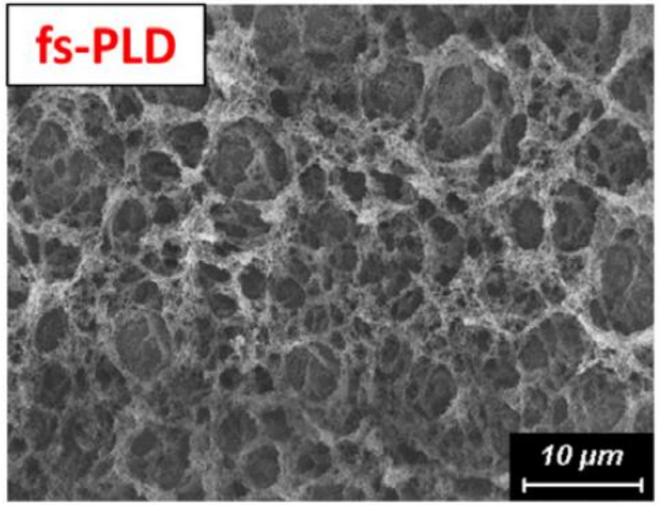
- Morphology
- Thickness *d*
- Composition c_i
- Mass density ρ



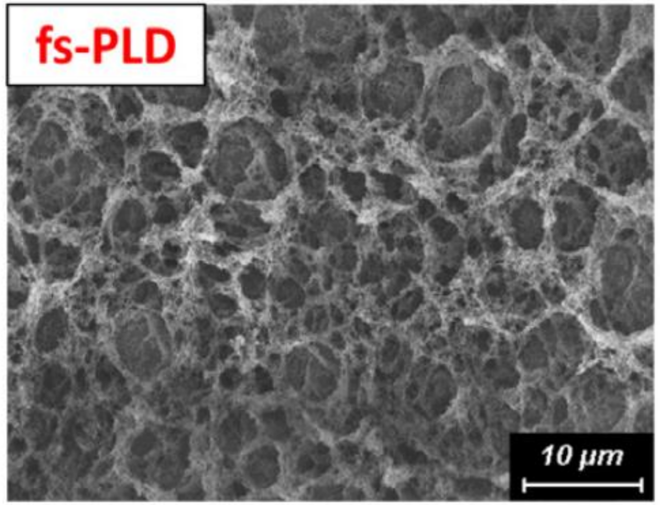
$$\frac{I_{i,foam}}{I_{sub}} = f(\rho, d, c_i, c_{i\neq j})$$

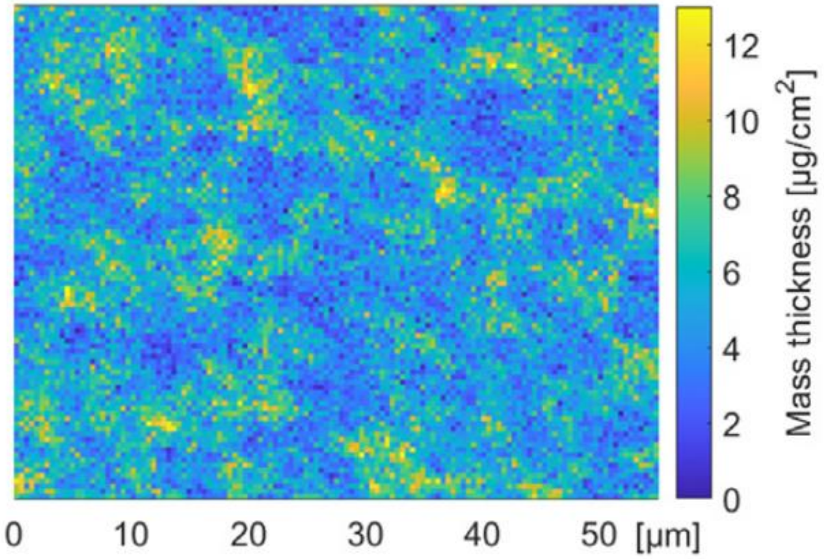
A. Pazzaglia et al., *Material Characterization* **153**, 92 (2019)

Fine tuning of nanofoam density

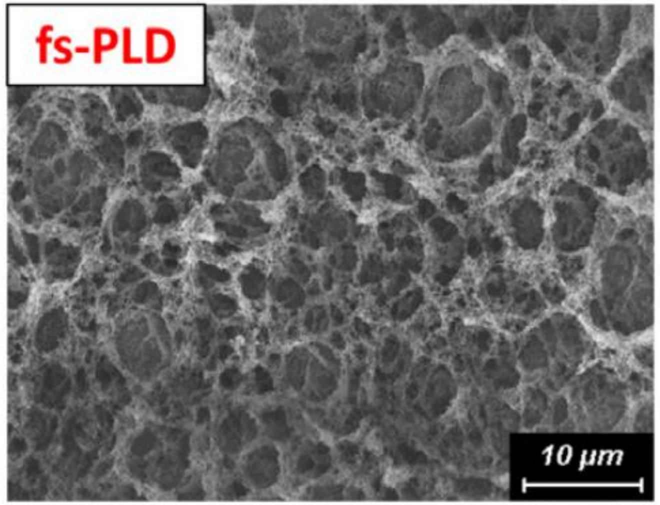


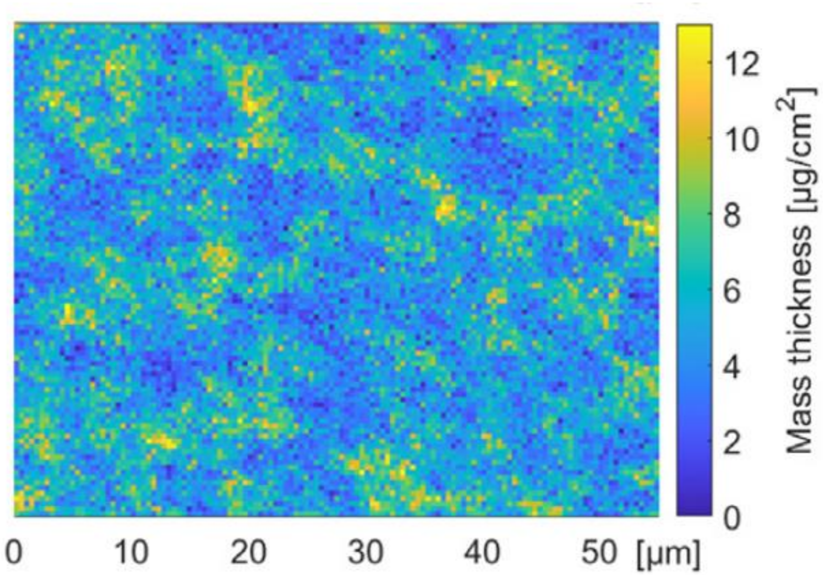
Fine tuning of nanofoam density

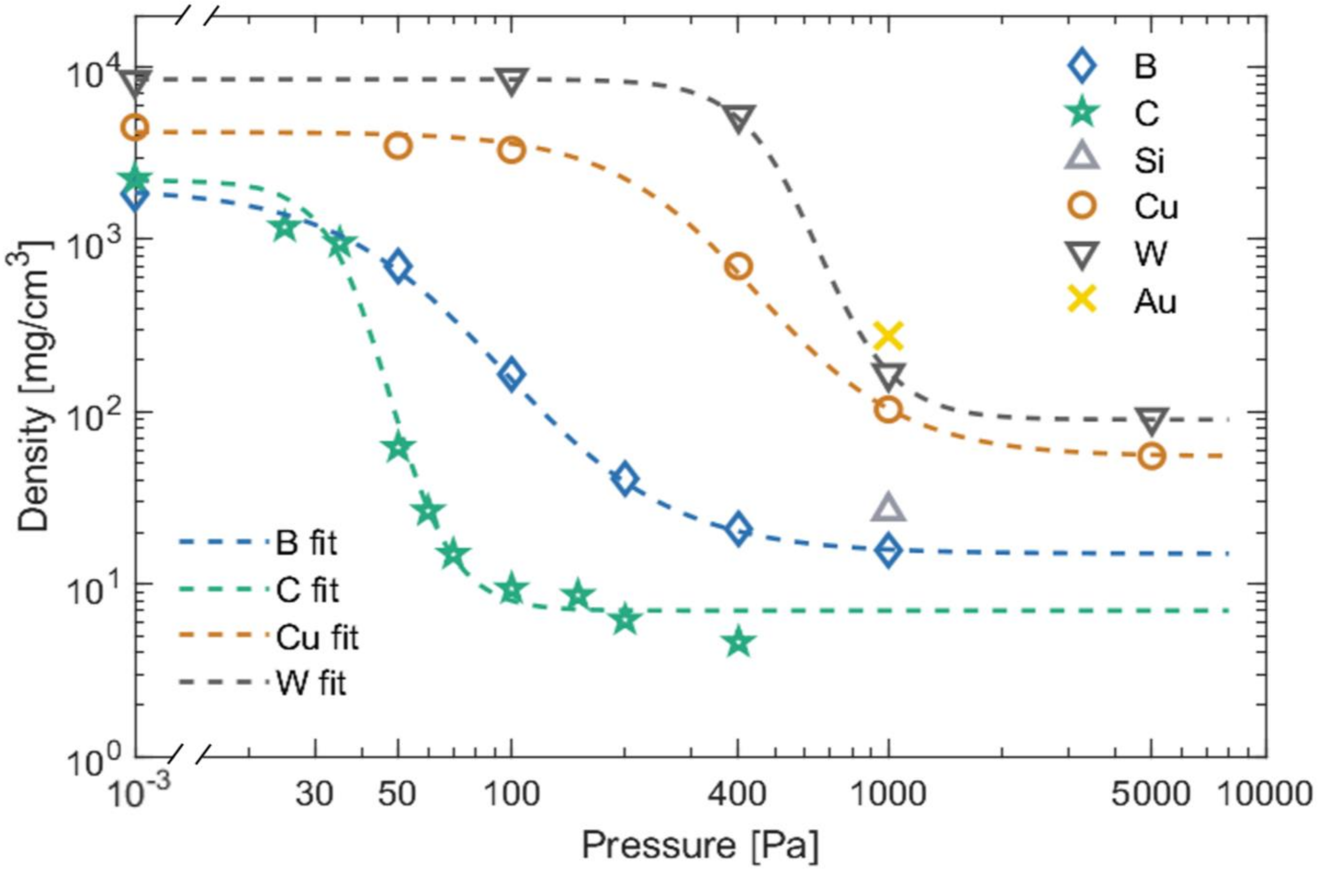




Fine tuning of nanofoam density

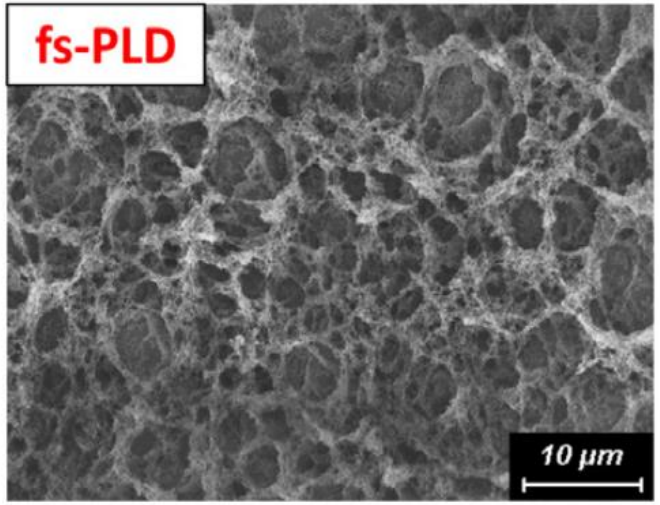


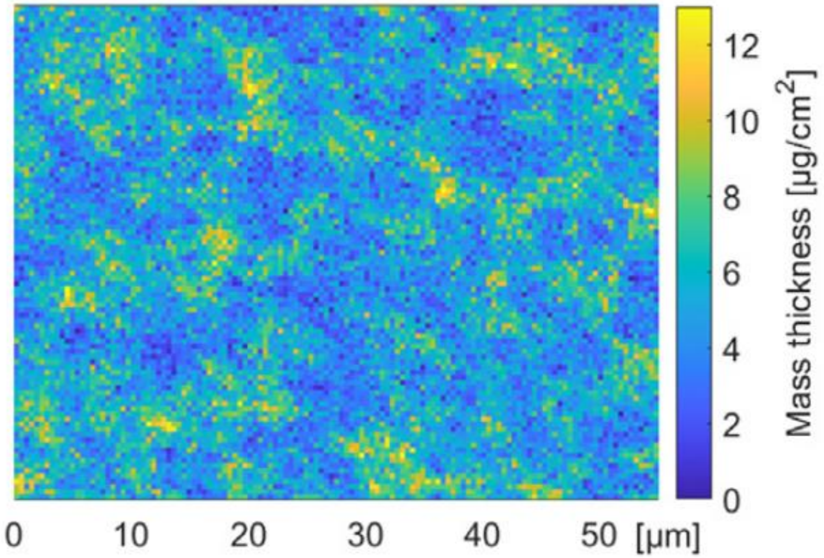




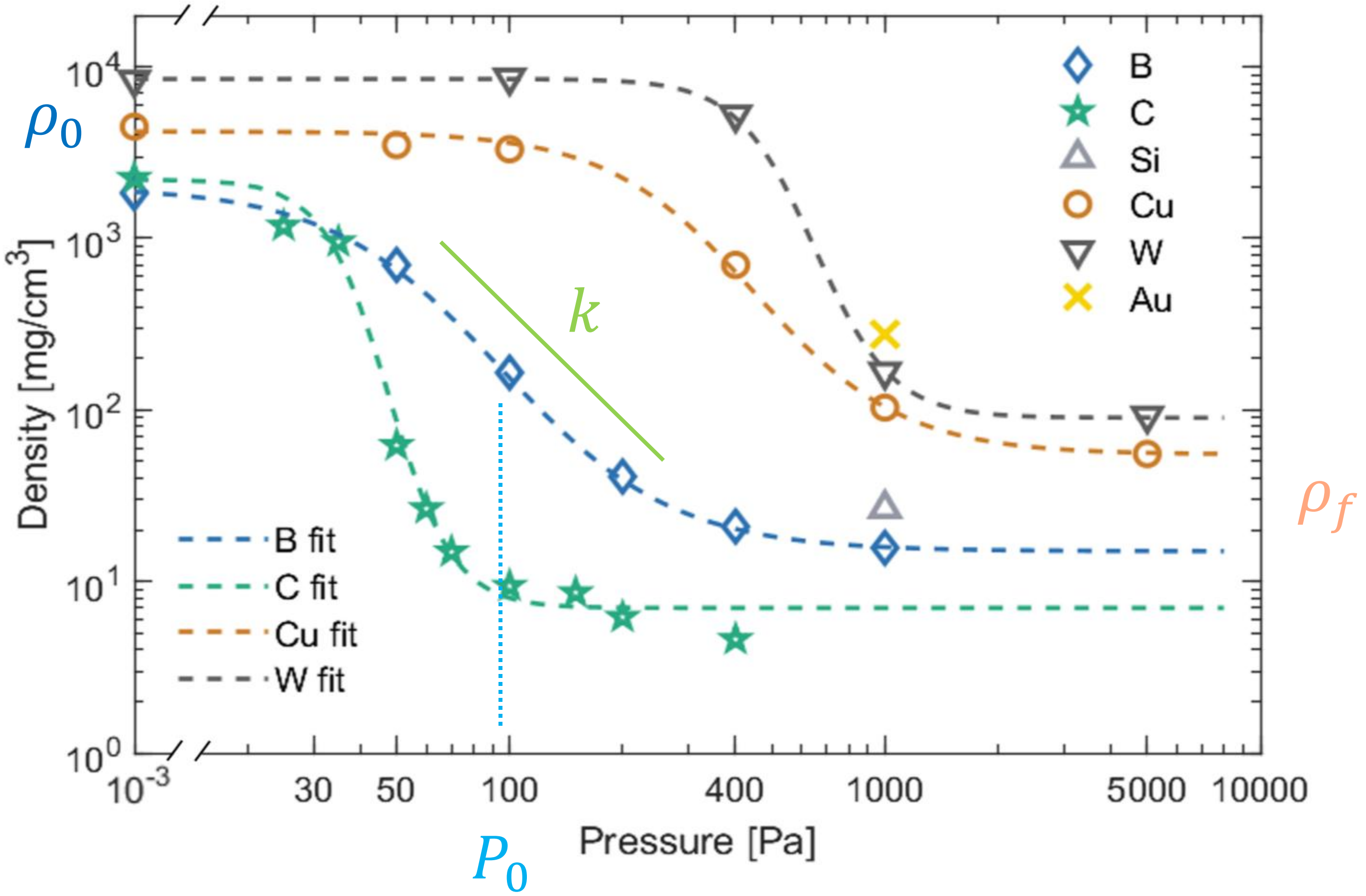
D. Orecchia et al., *Small Structures* **5**, 2024

Fine tuning of nanofoam density





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

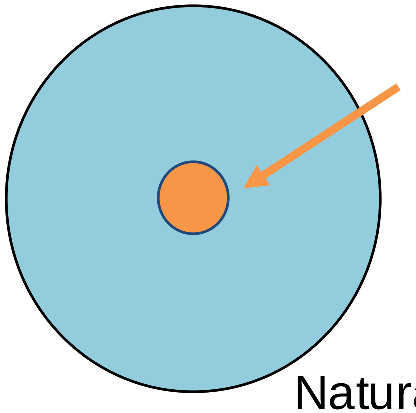


D. Orecchia et al., *Small Structures* **5**, 2024

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

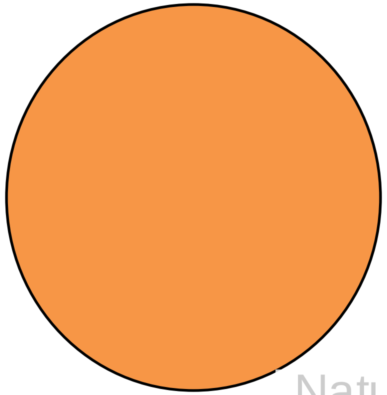
Hydrogenated born nanofoams

Heterogeneous target



Hydrogenated born nanofoams

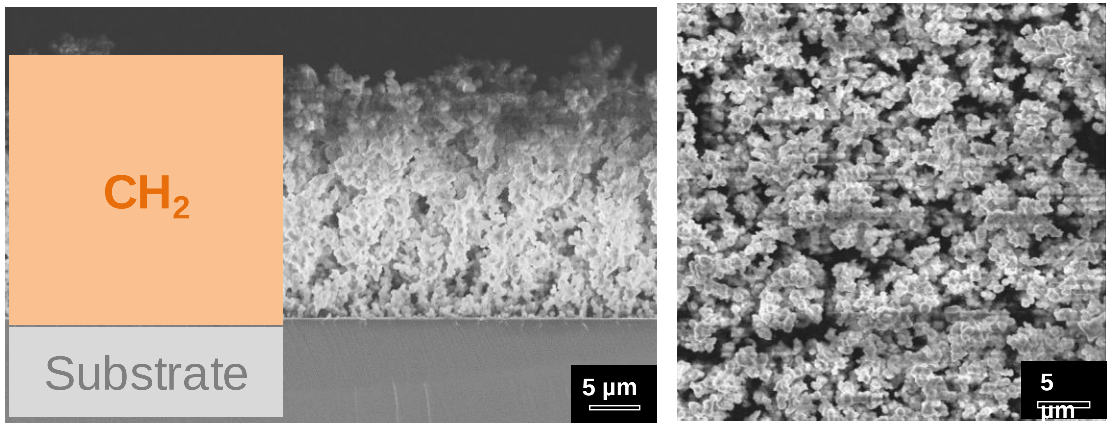
Heterogeneous target



HDPE $(CH_2)_n$
(Variable size)

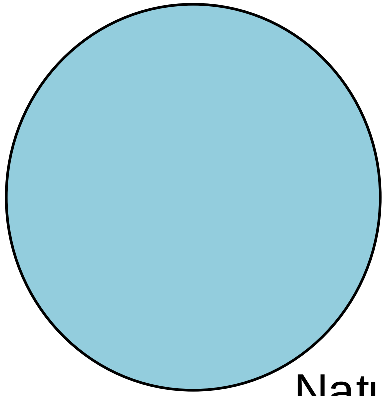
Natural **Boron**

CH_2 nanofoam



Hydrogenated born nanofoams

Heterogeneous target



HDPE $(CH_2)_n$
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Natural **Boron**

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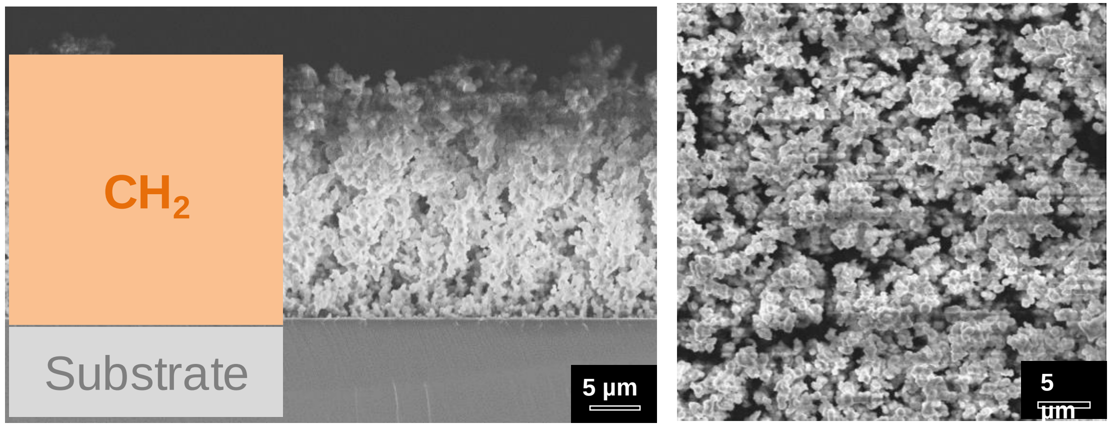
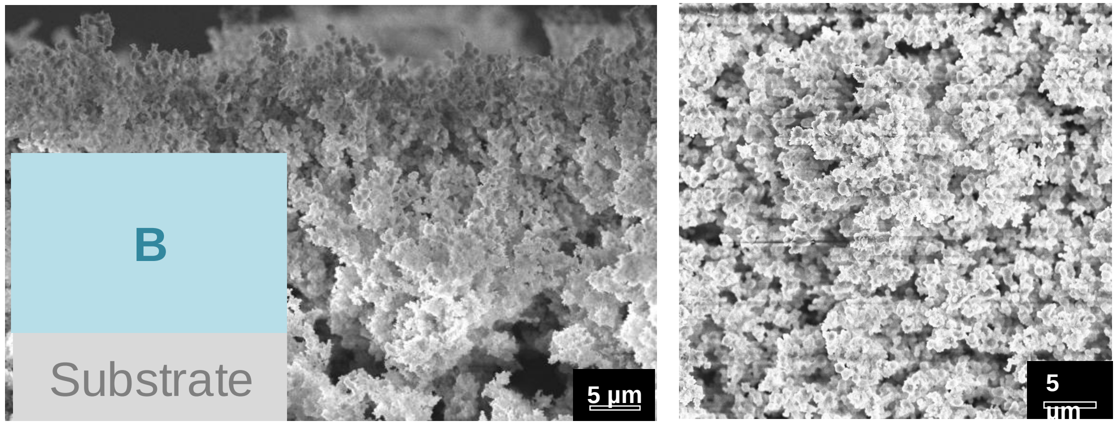
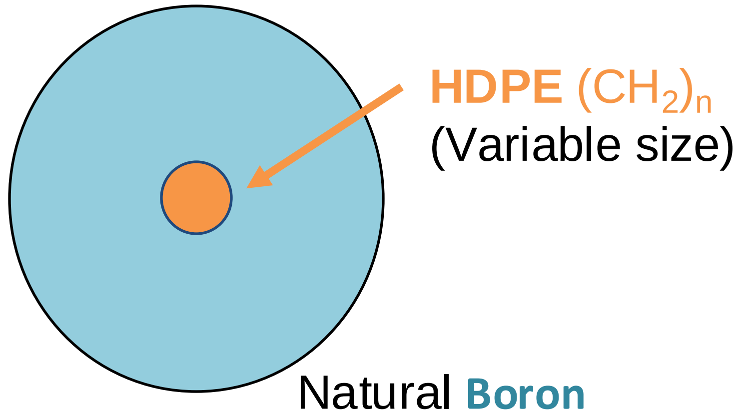


B multilayer

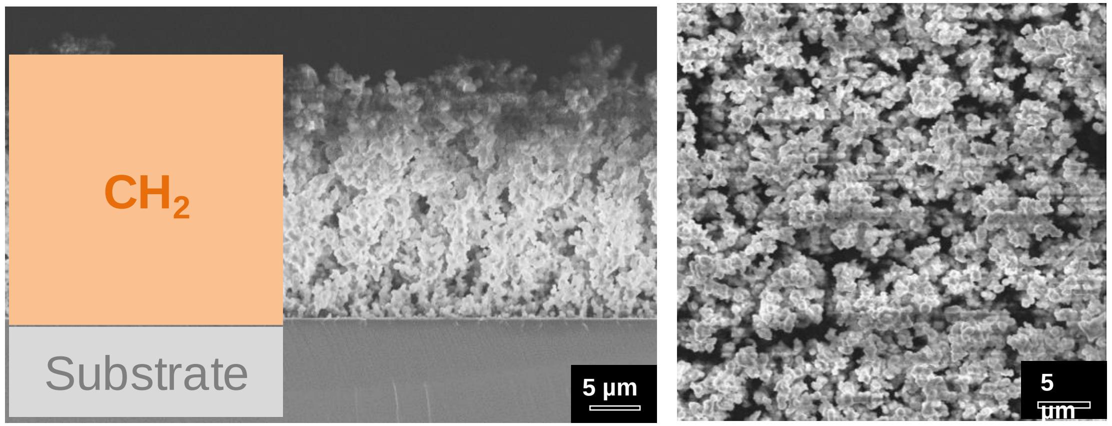


Hydrogenated born nanofoams

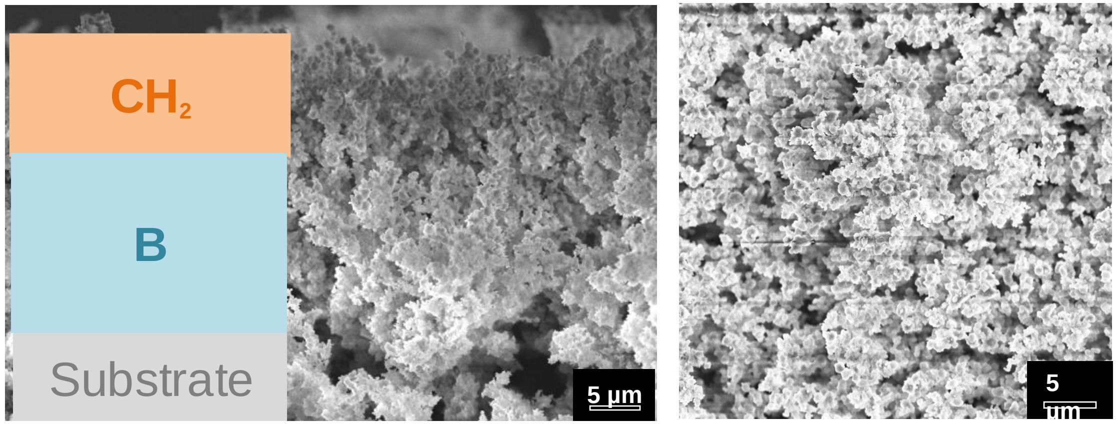
Heterogeneous target



CH_2 nanofoam

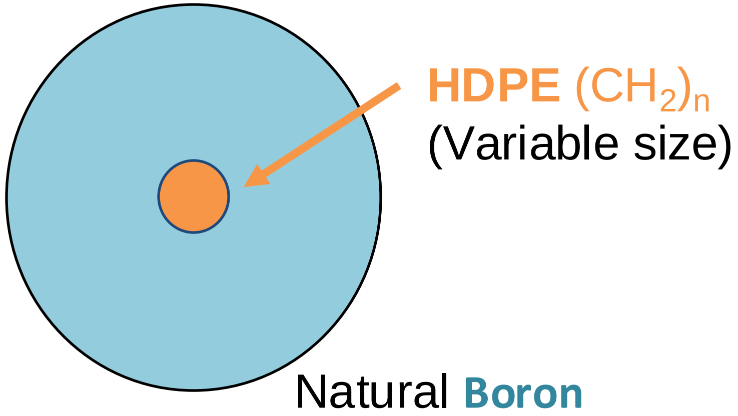


B / CH_2 multilayer

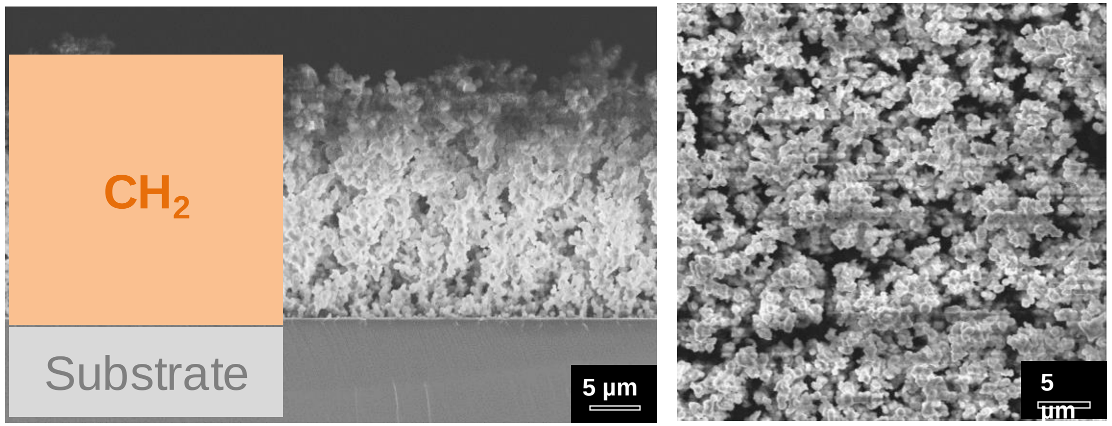


Hydrogenated born nanofoams

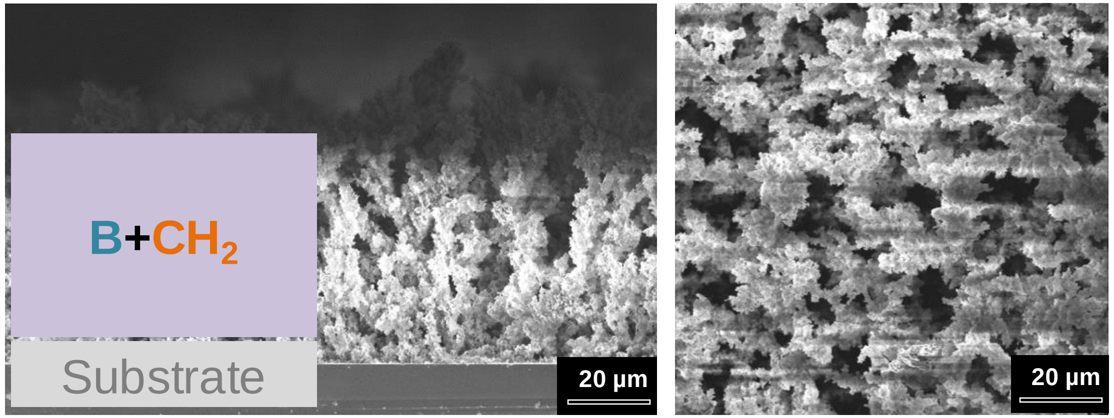
Heterogeneous target



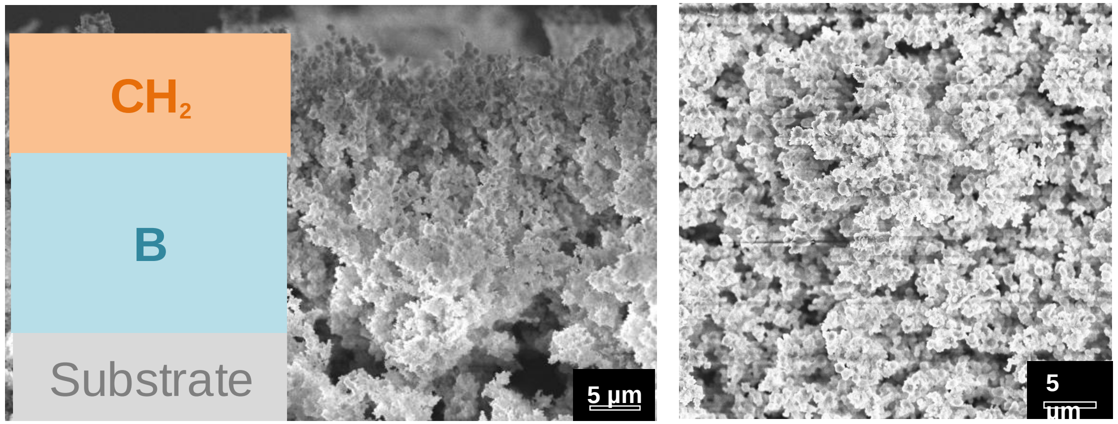
CH_2 nanofoam



B+CH_2 nanofoam

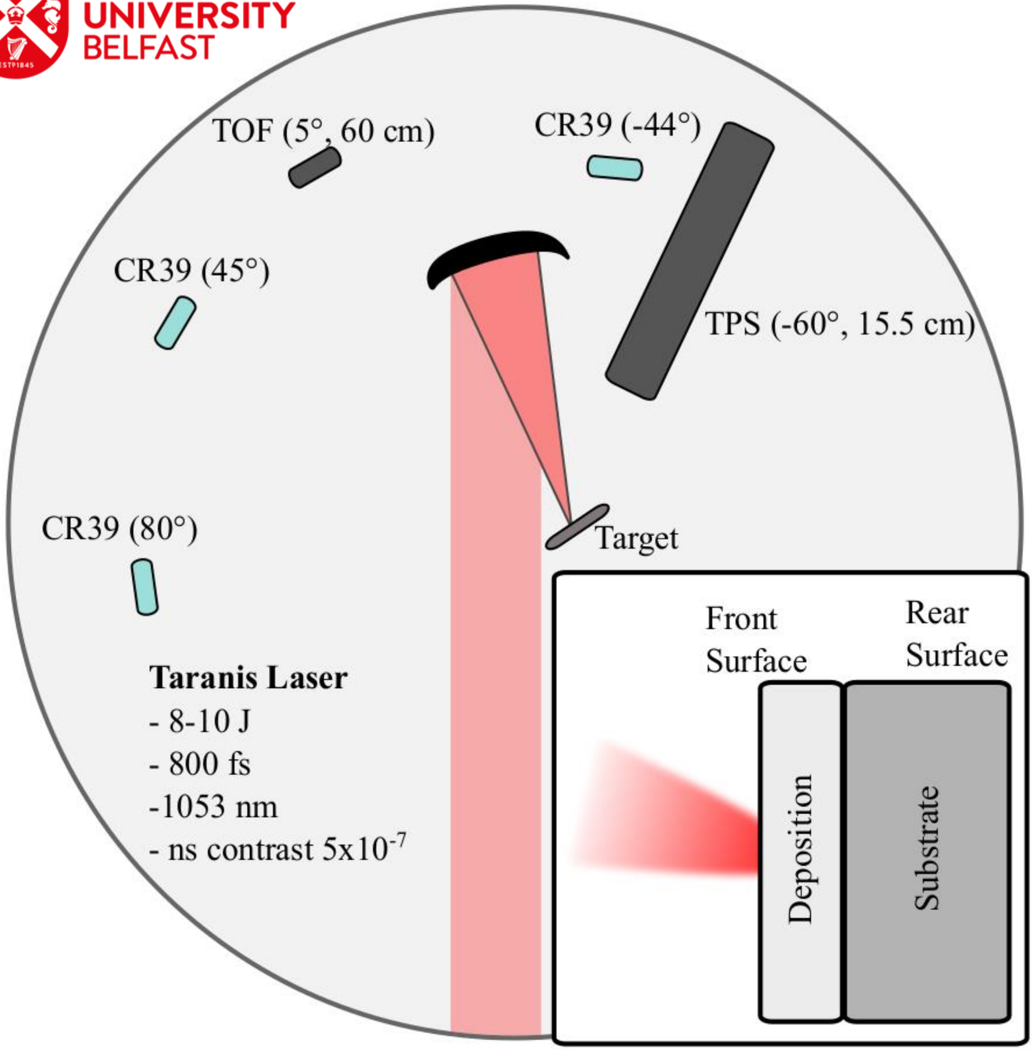


B / CH_2 multilayer



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

Nanofoams targets for experiment @ Taranis



D. Molloy et al., submitted to *Physical Review Research* (2024)

Nanofoams targets for experiment @ Taranis

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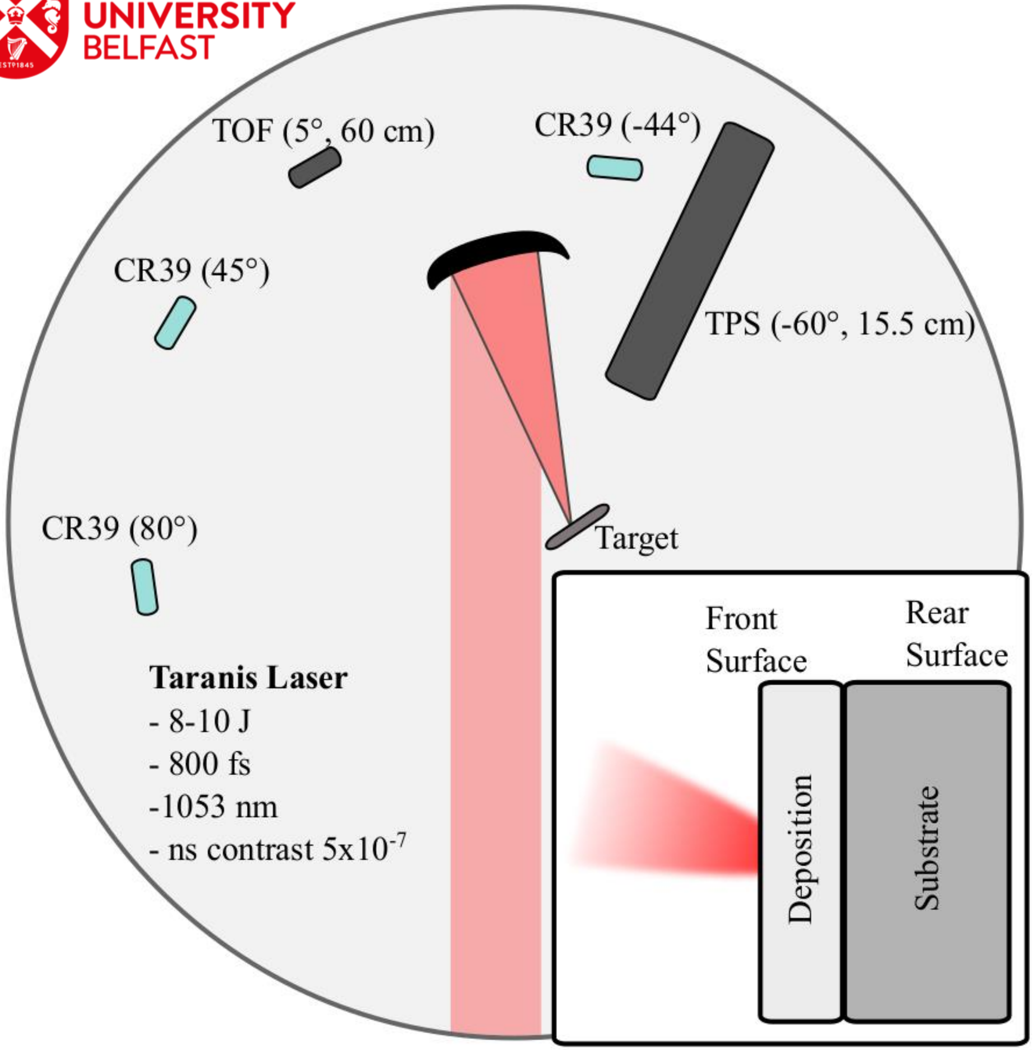
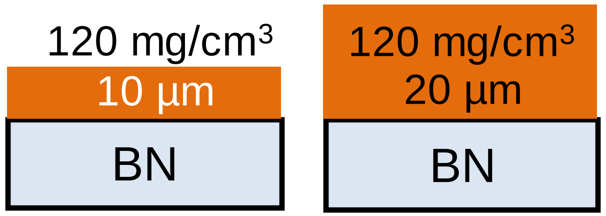


CH_2 nanofoam
on BN substrate



~60% H, ~30% C, ~10% O

D. Molloy et al., submitted to *Physical Review Research* (2024)

Nanofoams targets for experiment @ Taranis

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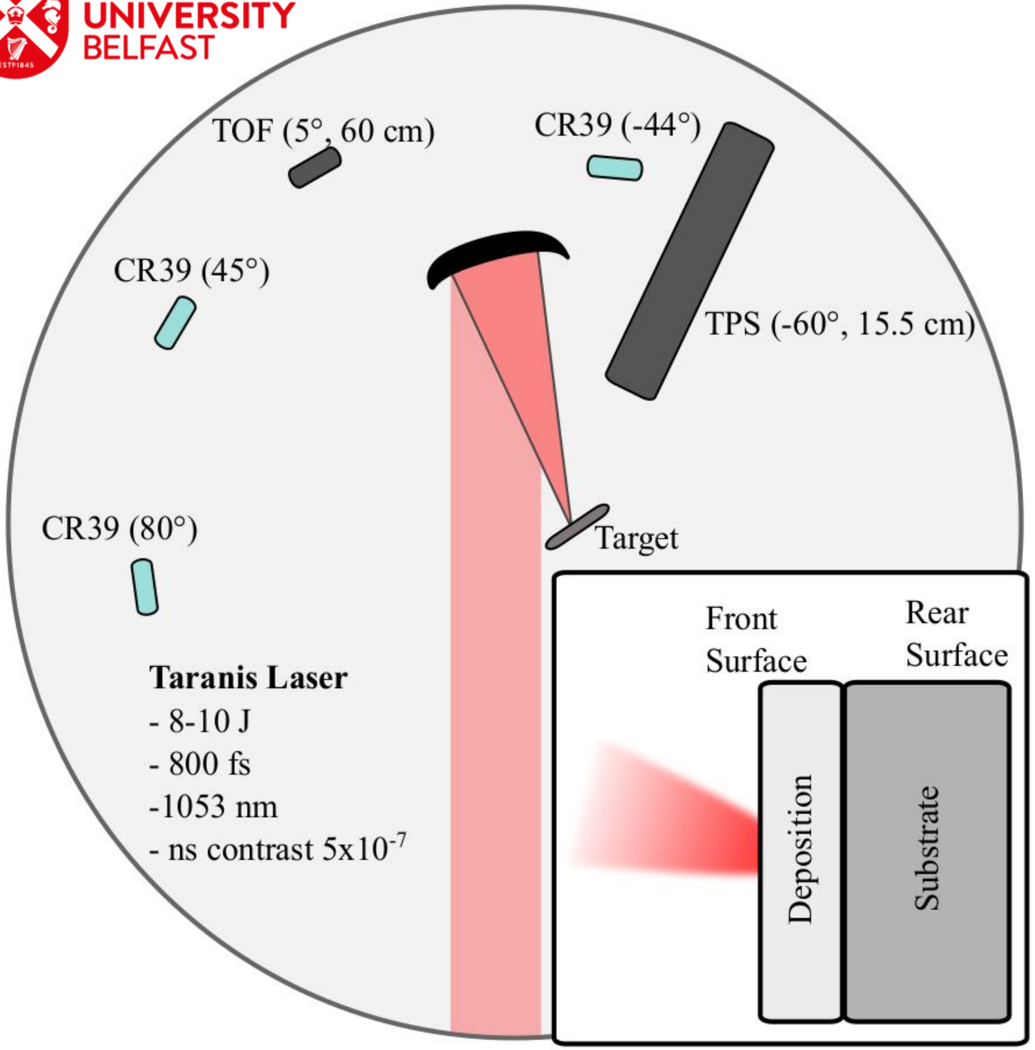


CH_2 nanofoam
on BN substrate

120 mg/cm^3 10 µm | BN

120 mg/cm^3 20 µm | BN

~60% H, ~30% C, ~10% O

B nanofoam
on PP substrate

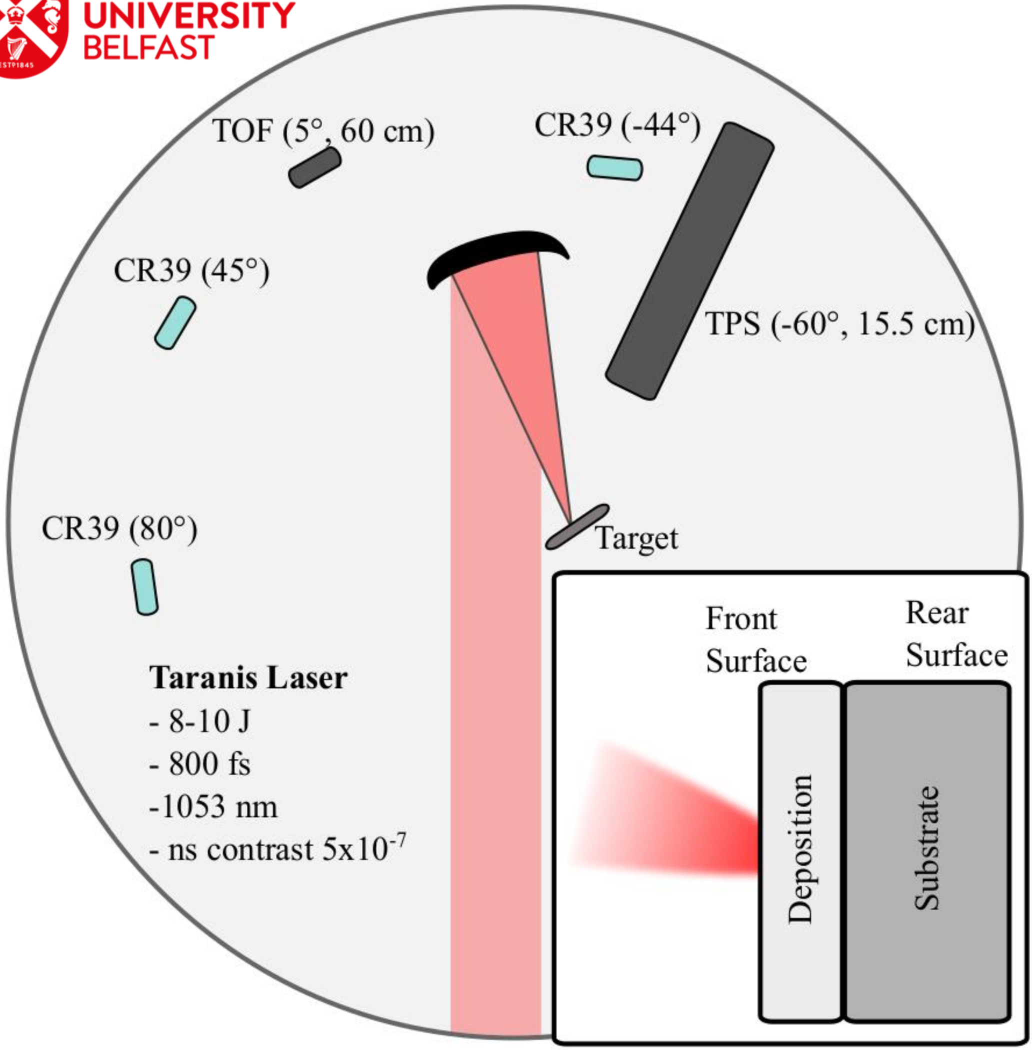
100 mg/cm^3 50 µm | PP

100 mg/cm^3 100 µm | PP

50 mg/cm^3 100 µm | PP

~85-90% B, ~10-15% O

Nanofoams targets for experiment @ Taranis



CH_2 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+CH_2 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

D. Molloy et al., submitted to *Physical Review Research* (2024)

Nanofoams targets for experiment @ Taranis

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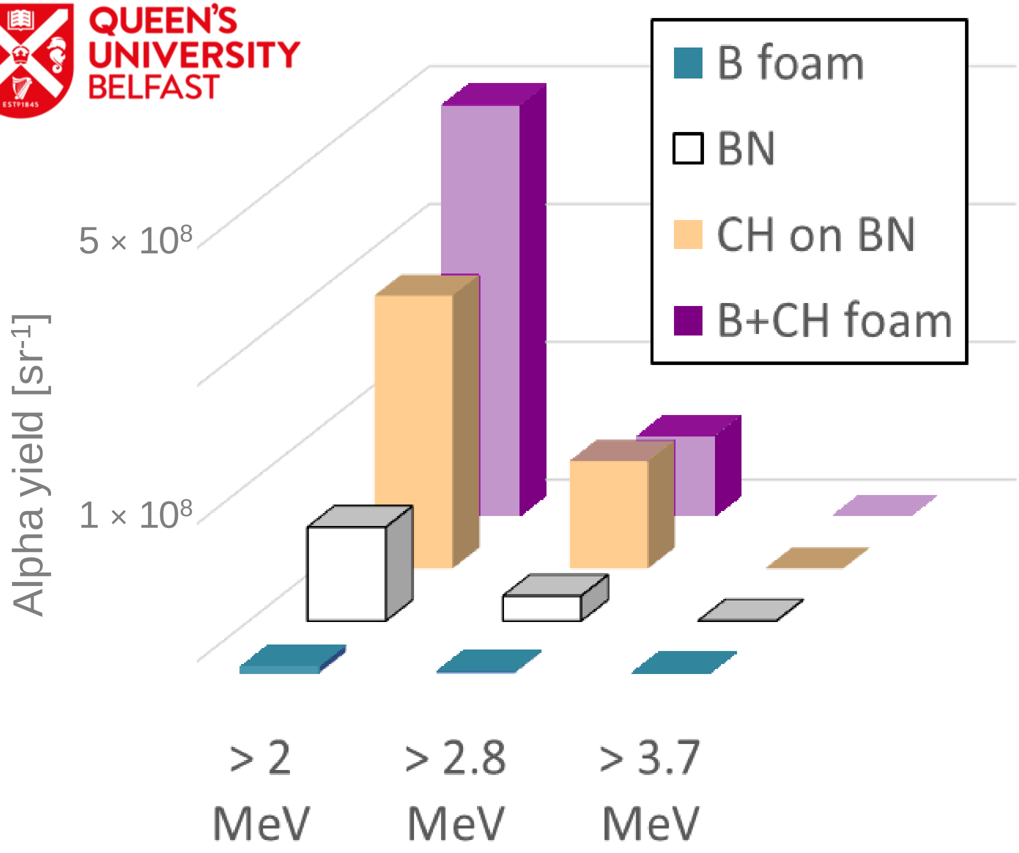

CH_2 nanofoam
on BN substrate

120 mg/cm³, 20 µm — BN
120 mg/cm³, 10 µm — BN

~60% H, ~30% C, ~10% O

B nanofoam
on PP substrate

100 mg/cm³, 50 µm — PP
100 mg/cm³, 100 µm — PP
50 mg/cm³, 100 µm — PP

~85-90% B, ~10-15% O

$B+CH_2$ nanofoam
on PP substrate

80 mg/cm³, 60 µm — PP
40 mg/cm³, 100 µm — PP

~40% H, ~30% B, ~20% C, ~10% O

D. Molloy et al., submitted to *Physical Review Research* (2024)

Nanofoams targets for experiment @ Taranis

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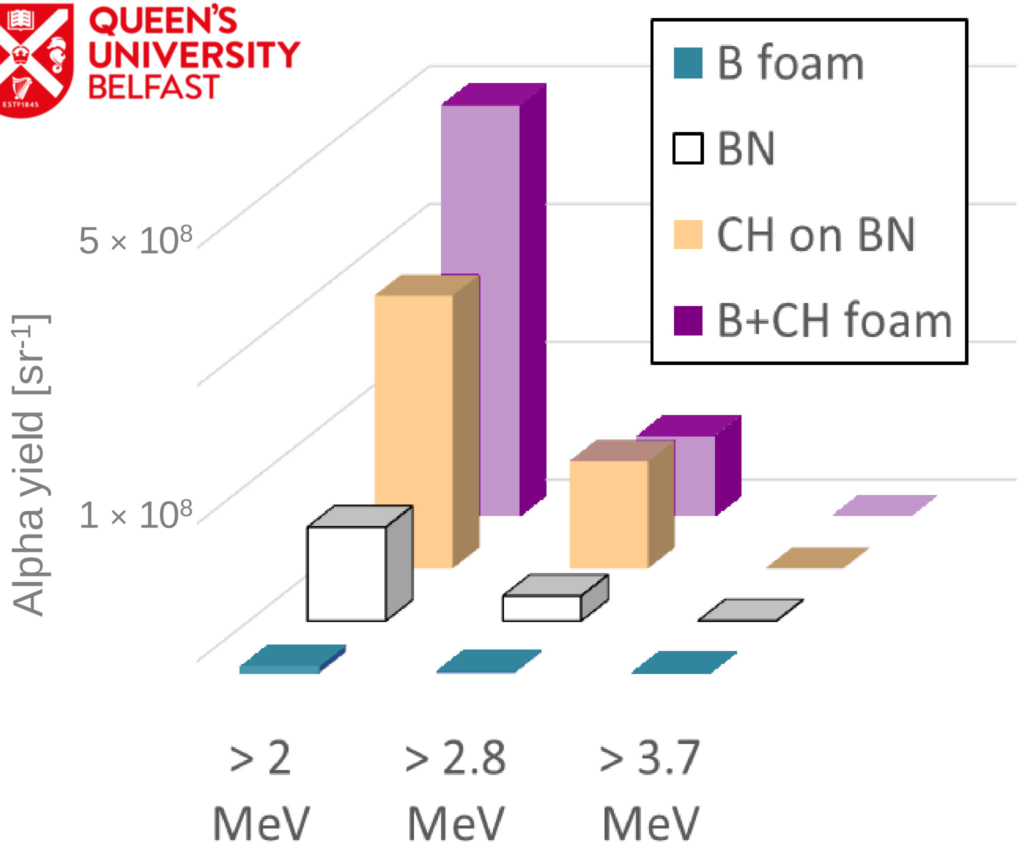


In-foam proton-boron fusion reactions

CH_2 nanofoam on BN substrate

120 mg/cm^3 20 µm — BN

120 mg/cm^3 10 µm — BN

~60% H, ~30% C, ~10% O

B nanofoam on PP substrate

100 mg/cm^3 50 µm — PP

100 mg/cm^3 100 µm — PP

50 mg/cm^3 100 µm — PP

~85-90% B, ~10-15% O

B+CH_2 nanofoam on PP substrate

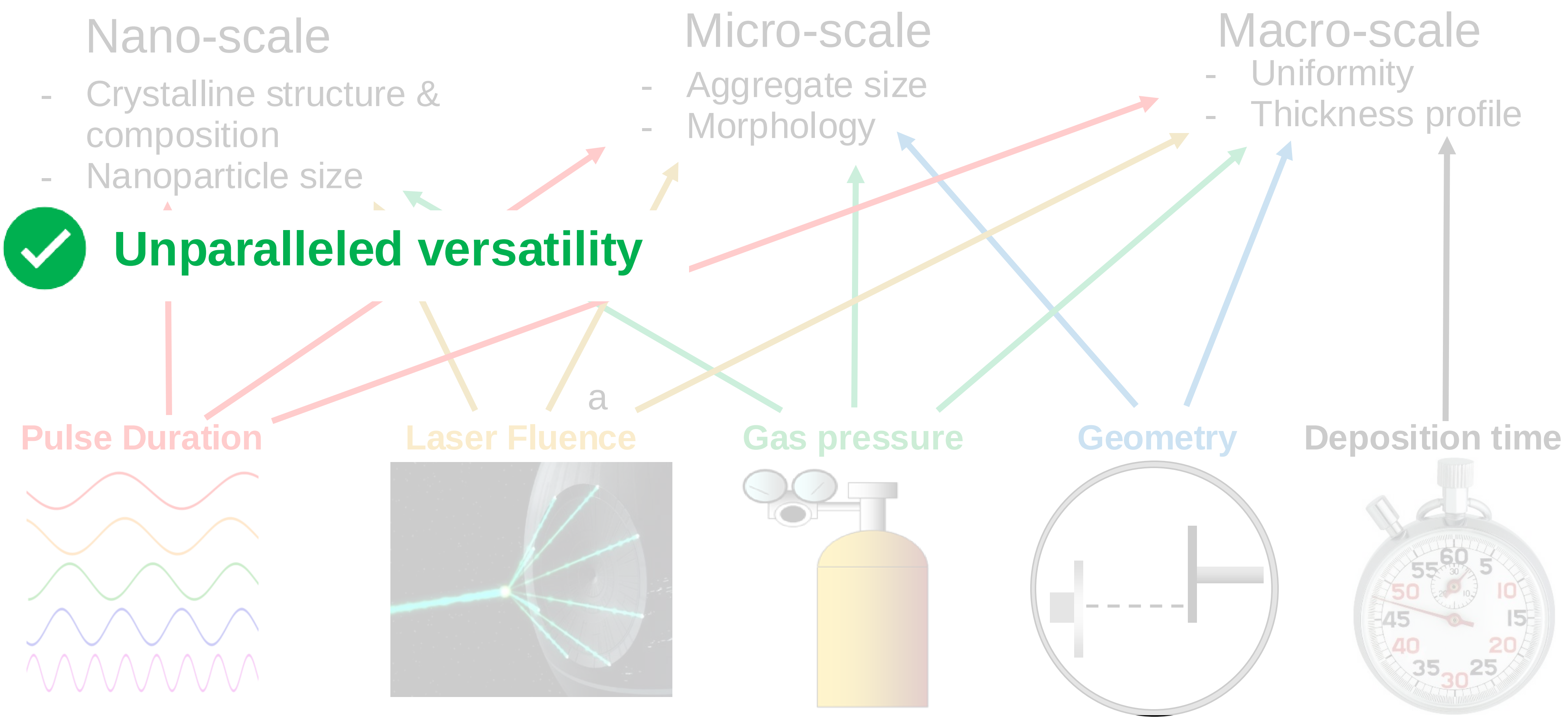
80 mg/cm^3 60 µm — PP

40 mg/cm^3 100 µm — PP

~40% H, ~30% B, ~20% C, ~10% O

D. Molloy et al., submitted to *Physical Review Research* (2024)

In conclusion



Unparalleled versatility

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

a

Pulse Duration

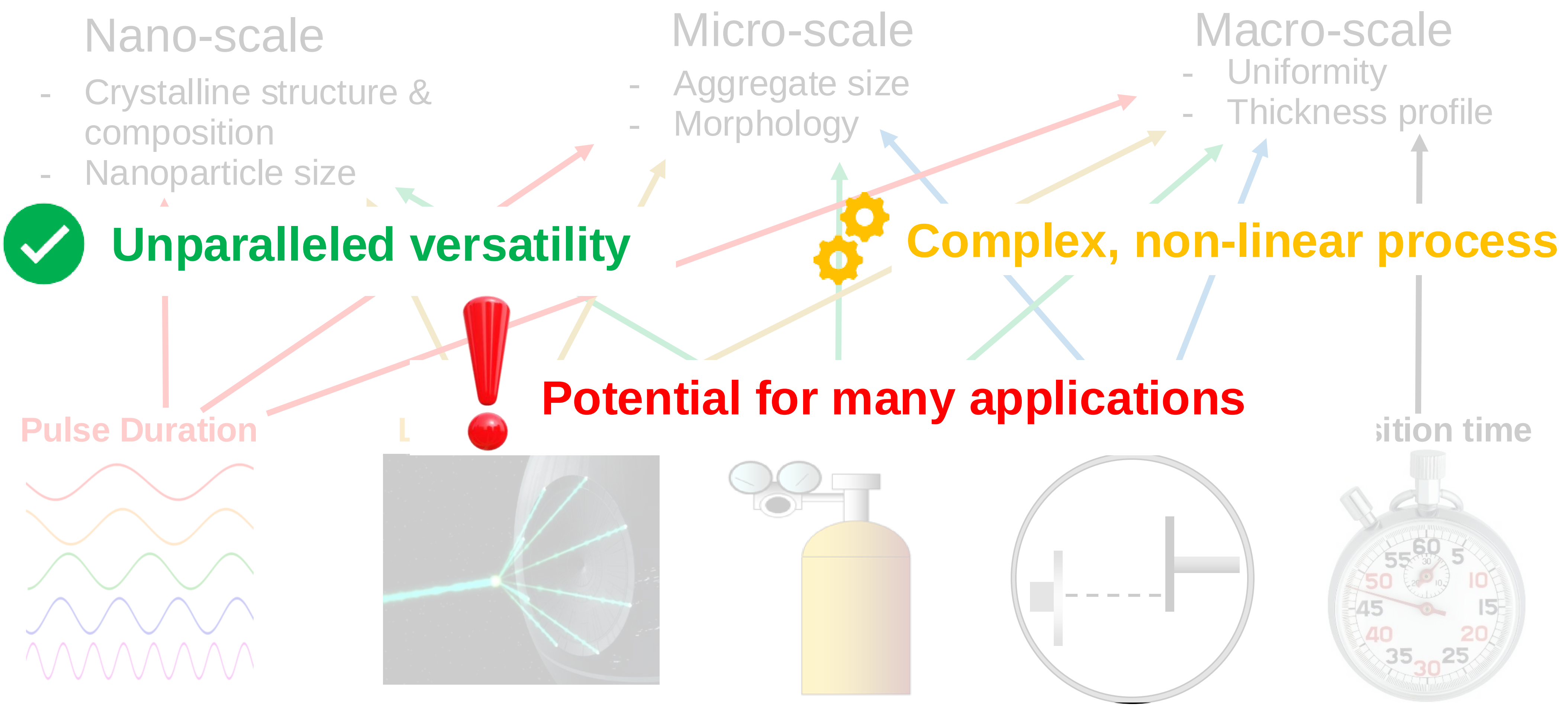
Laser Fluence

Gas pressure

Geometry

Deposition time

In conclusion

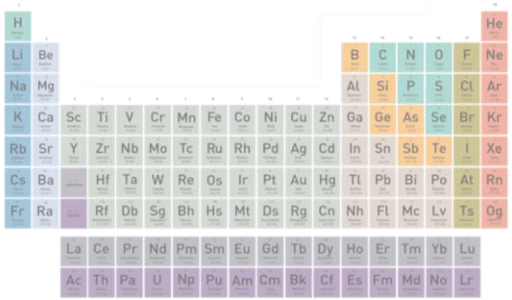


Unparalleled versatility

Complex, non-linear process

Potential for many applications

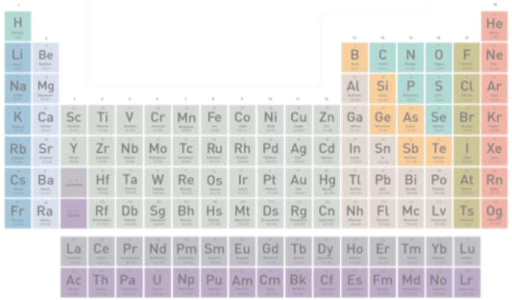
…What is coming next



1

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

…What is coming next



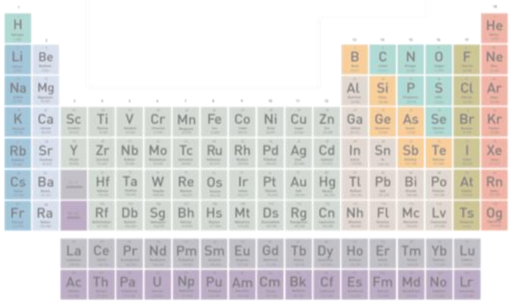
1

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

2

Nanofoam **optimization** according to laser parameters

…What is coming next



1

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

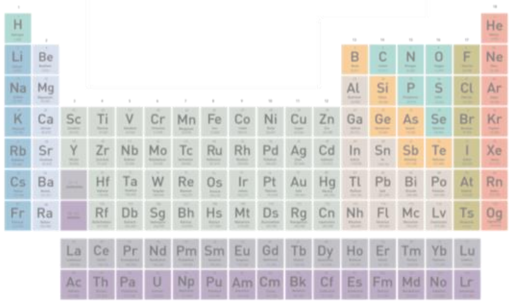
2

Nanofoam **optimization** according to laser parameters

3

Advanced targets for future **experiments**

...What is coming next



1

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

2

Nanofoam **optimization** according to laser parameters

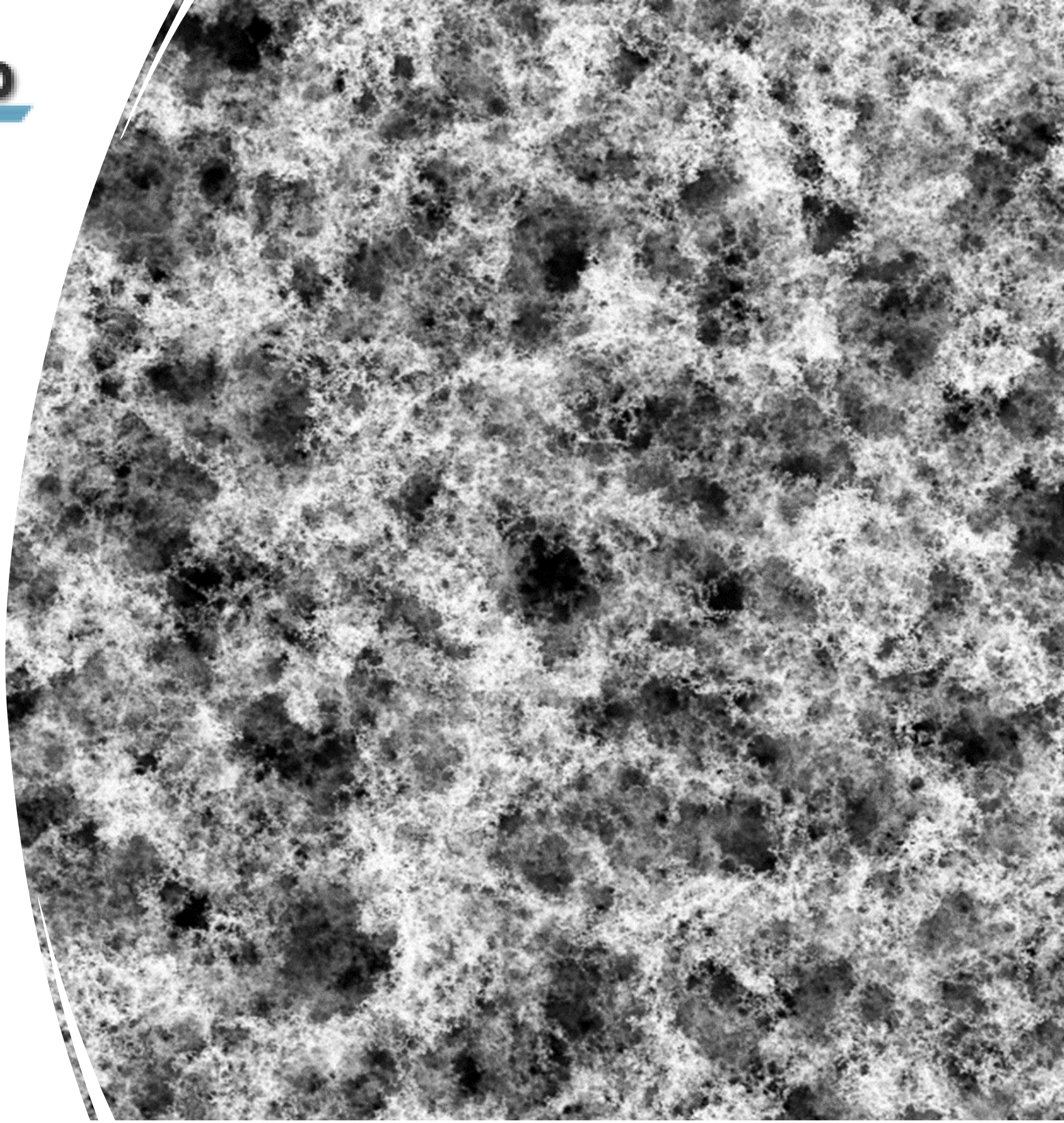
3

Advanced targets for future **experiments**

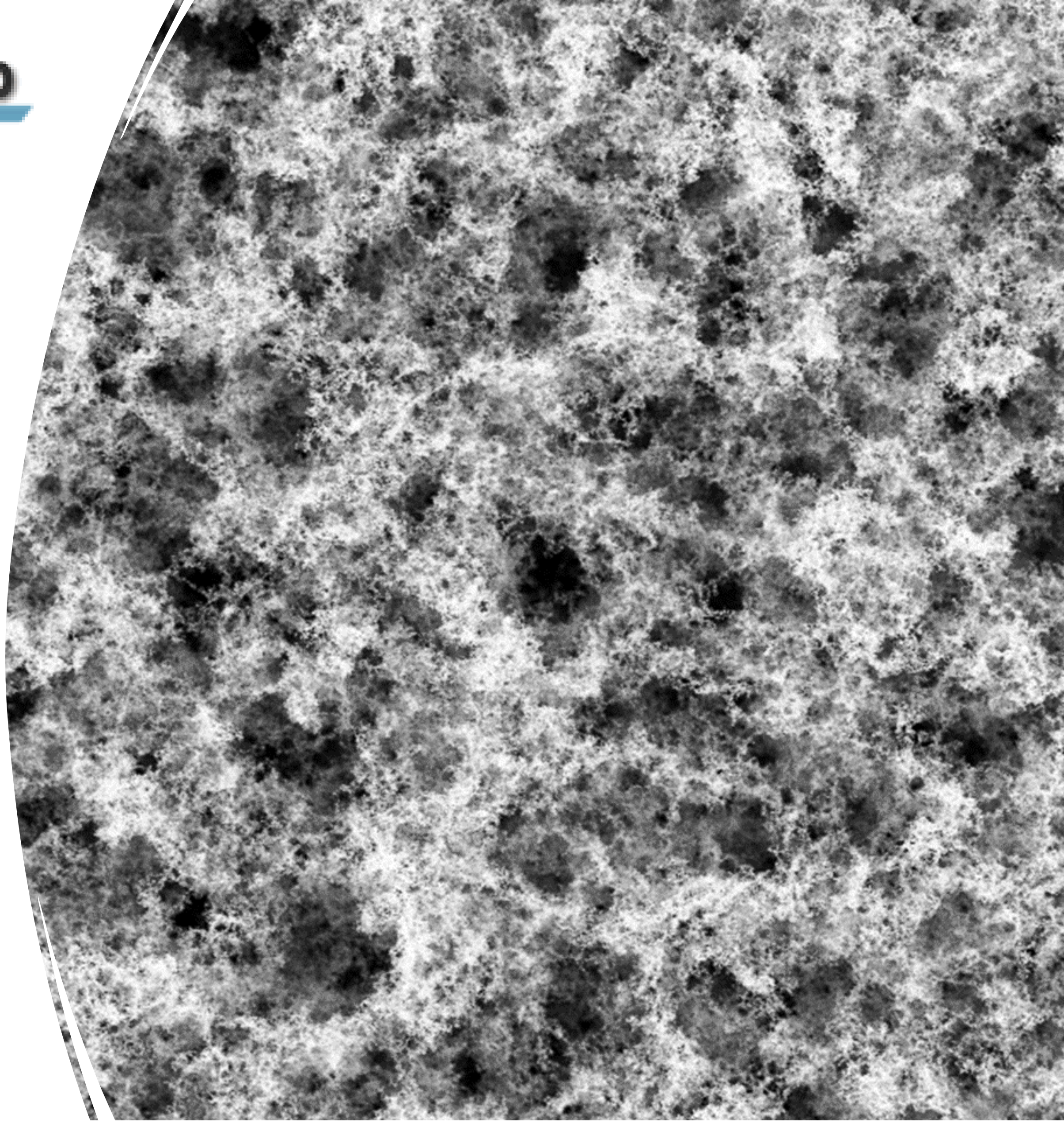
4

Your suggestions!

NanoLab



POLITECNICO
MILANO 1863



PRIN 2022 programme
NANOMATERIALS FOR FUSION
CUP D53D23002840006

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FUSION — FUsion StudIes of prOton boron Neutronless reaction in laser-generated plasma

CA 21128 PROBONO

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CUP D53D23002840006

Thank you for your attention!