3rd International Workshop on Proton-Boron Fusion

Prague, 4/10/2023

POLITECNICO
MILANO 1863

Advancements in Pulsed Laser Deposition of boron-based targets for p-^{11}B studies

Orecchia D., *Vavassori D., Maffini A., Milani A., Dellasega D., Russo V., Zavelani-Rossi M., Mazzucconi D., Agosteo S., Pola A., Bortot D., Passoni M.*

EUROfusion

NanoLab

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Overview

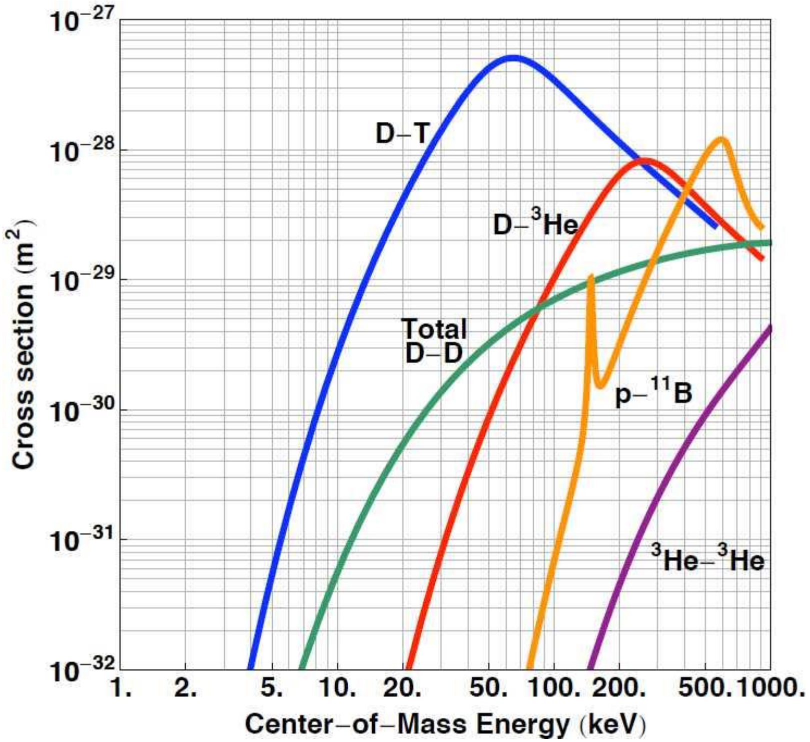
- Introduction
- Targets for p-^{11}B studies
- Pulsed Laser Deposition (PLD) as a flexible technique
- Compact boron films
  - Application to p-^{11}B cross section studies
- Low density boron nanofoams
- Conclusion and perspectives

Proton-boron fusion

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

Aneutronic reaction

Different **applications**



laser driven fusion schemes

Yield advances in recent years

laser technology advances

+

Target development

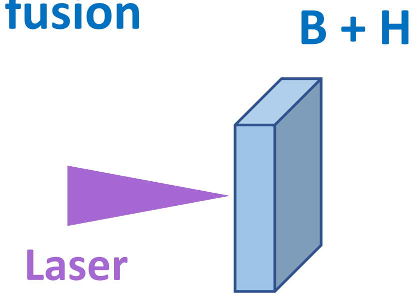
Margarone D. et al., Applied Sciences 12.3, 2022

Targets for p-^{11}B studies

Different targets for **different aims**

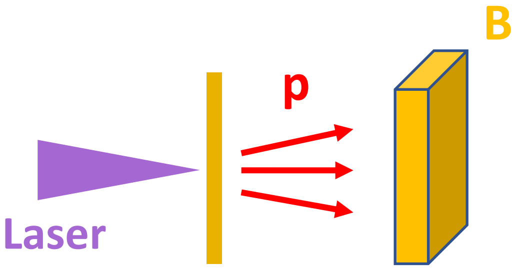
1

Direct irradiation p-B fusion



2

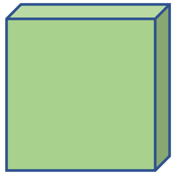
Pitcher-catcher p-B fusion



3

p-B cross-section studies

Solid targets with **well controlled** properties

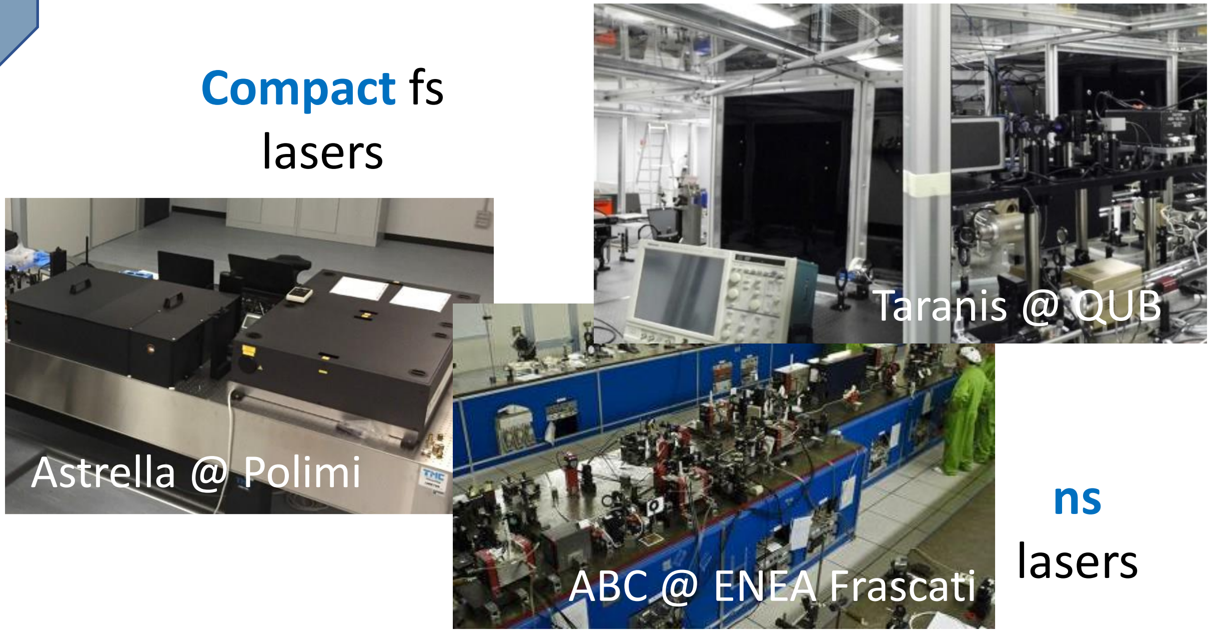


Fundamental for **understanding the physics**

sub-ps lasers

Compact fs lasers

ns lasers

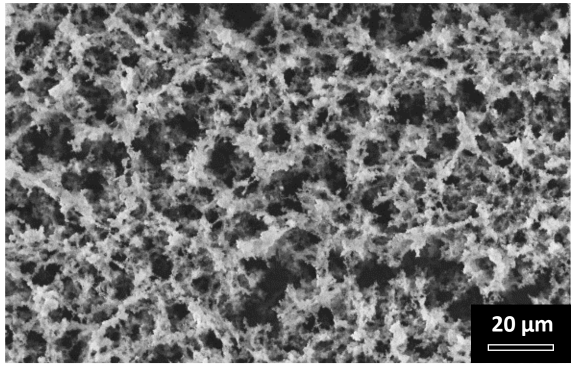


Nanostructured low-density targets

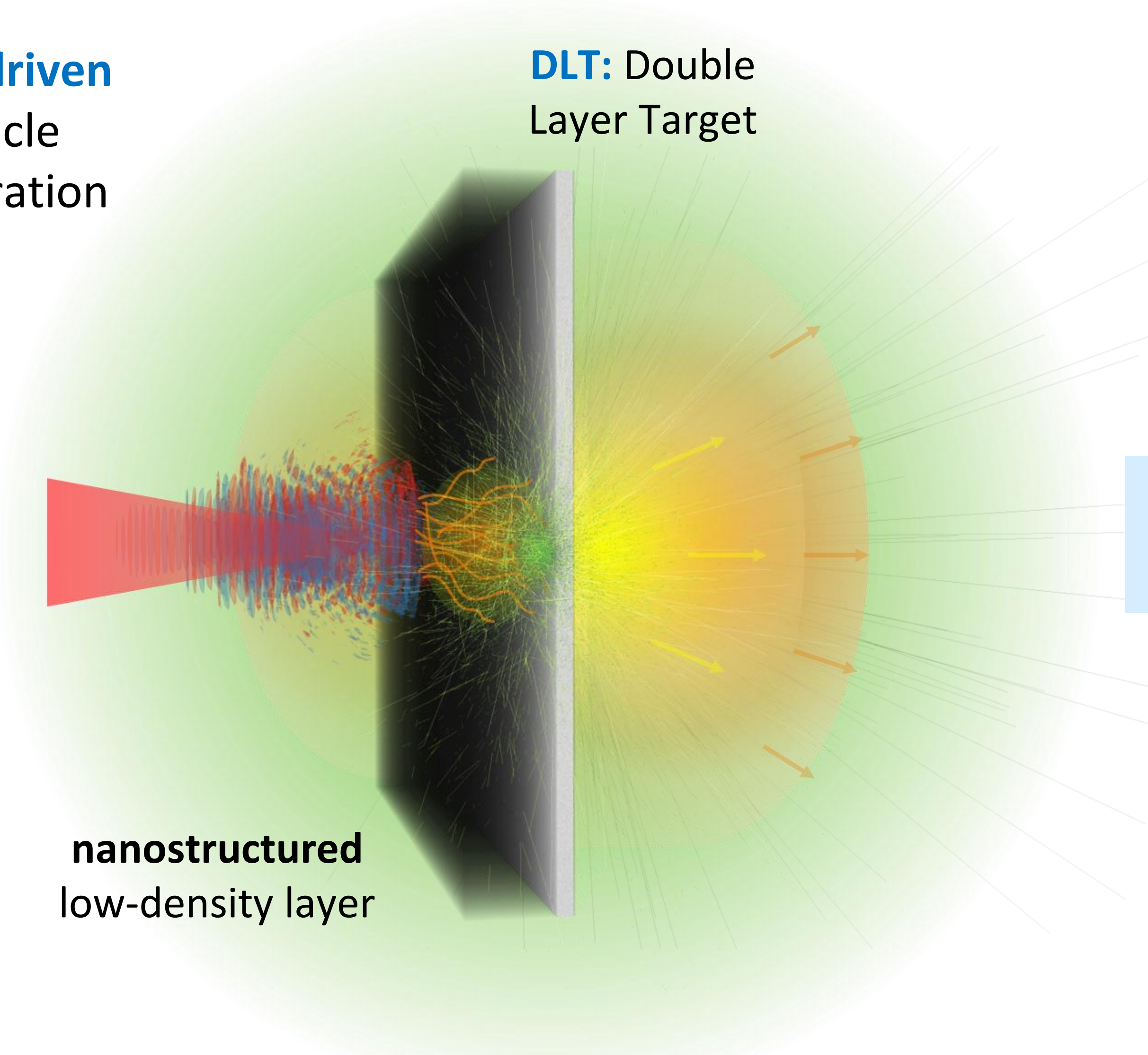
Passoni M. et al., Plasma Physics and Controlled Fusion 62, 2019

Laser-driven p-B fusion ⇔ **Laser-driven** particle acceleration

Nanofoams



How to produce them?



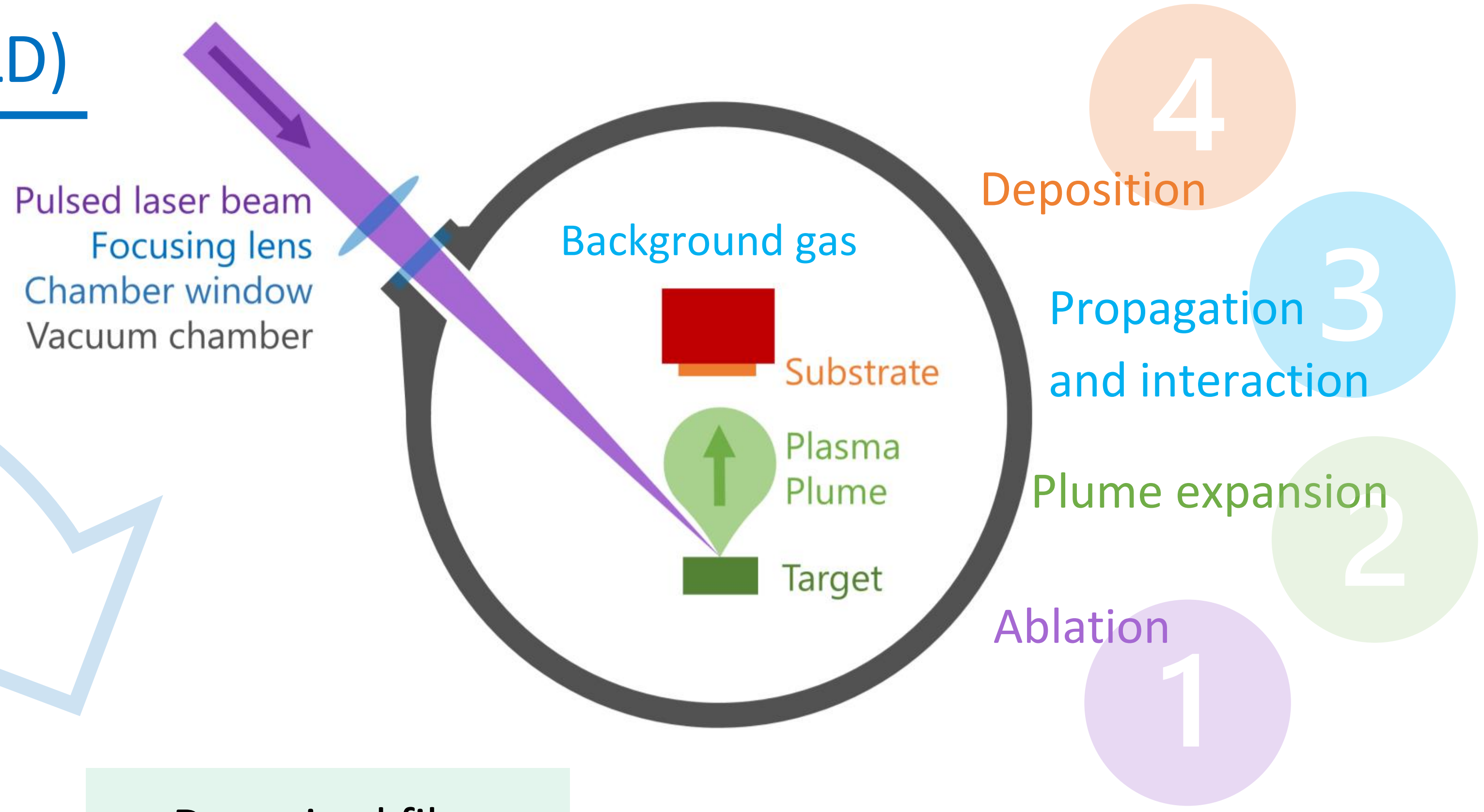
Near-critical nanostructured materials

⇓

Enhanced laser-matter interaction

- Self-focusing
- Coulomb explosion
- **Volumetric** laser-matter interaction

Pulsed Laser Deposition (PLD)



Process parameters

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

Deposited film
properties control

(density, thickness, elemental composition)

Laser **pulse duration**

ns-PLD

Well established

fs-PLD

Nonstandard

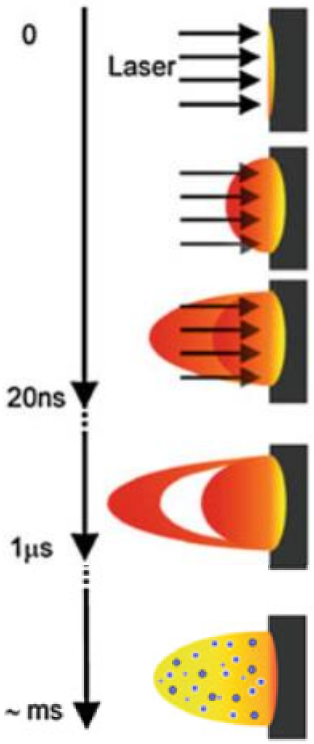
Flexible technique

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

ns-PLD vs fs-PLD

Different ablation regimes

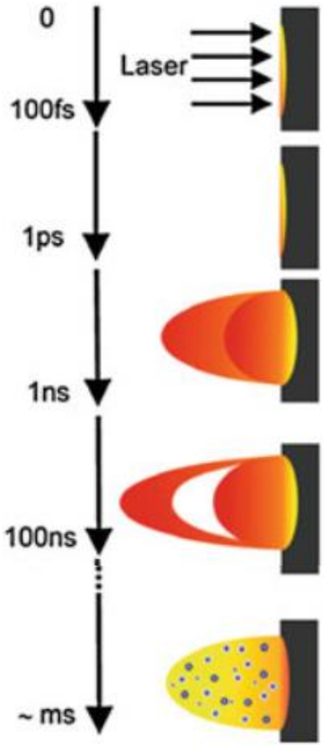
Nanosecond	**Femtosecond**



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

Plasma expansion

Plume condensation



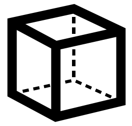
Electronic ablation of **nanoparticles**

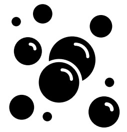
Plasma expansion

Plume condensation

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

ns-PLD	**fs-PLD**
⇩	⇩
Compact solid density films	**Foam-like** low density materials





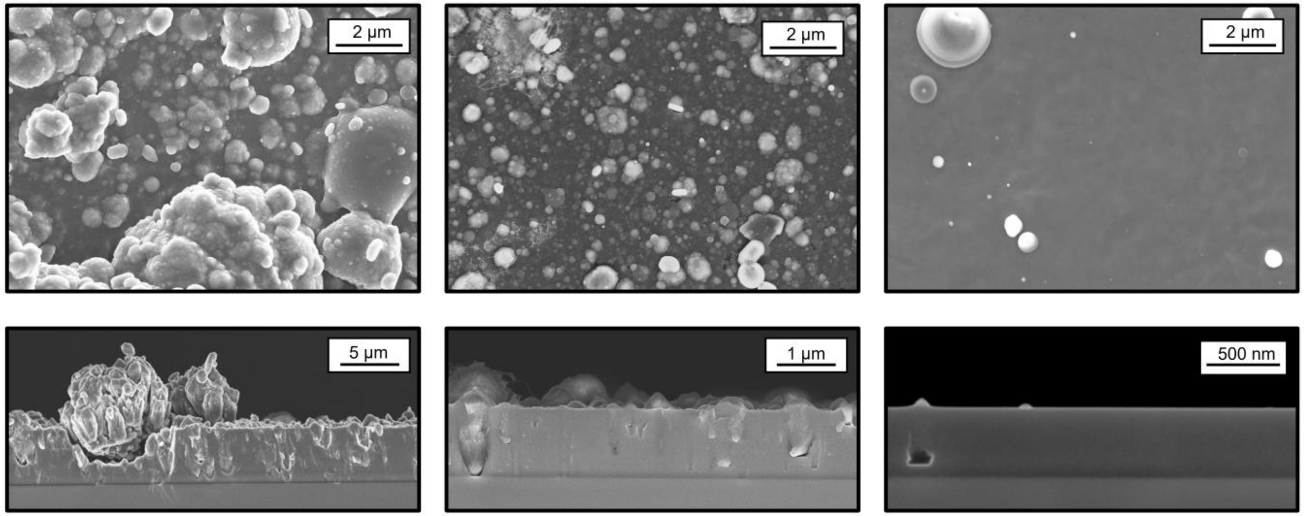
ns-PLD		fs-PLD
✓	Elemental flexibility	✓
✗	Heating issues	⚙

ns-PLD		fs-PLD	
⚙	Droplets	Nanopartices	✓
⚙	Stresses	Film stability	✗
✓	Reliable	Challenging	⚙

Complementary techniques

Compact boron films with ns-PLD

Target-substrate distance



Droplets

Deposition rate

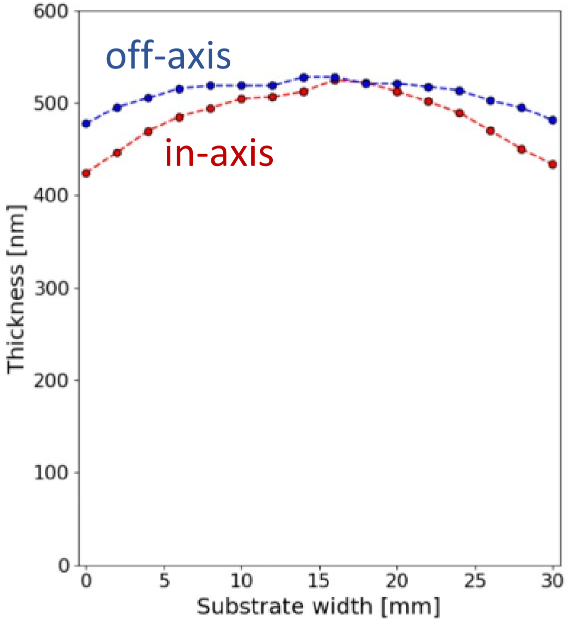
Deposition parameters:

- **ns-PLD** (532 nm, 7 ns)
- High vacuum ($10^{-3} - 10^{-4}$ Pa)
- High fluence ($8 - 9$ J/cm^2)
- Tradeoff target-substrate distance ($6 - 9$ cm)

Film properties:

- Solid density (~ 2.35 g/cm^3)
- Compact film with few defects
- Amorphous with residual stress state
- $100s$ nm $- 10$ µm thickness
- Oxidation and Mg impurities

Thickness **uniformity** & target **movimentation**

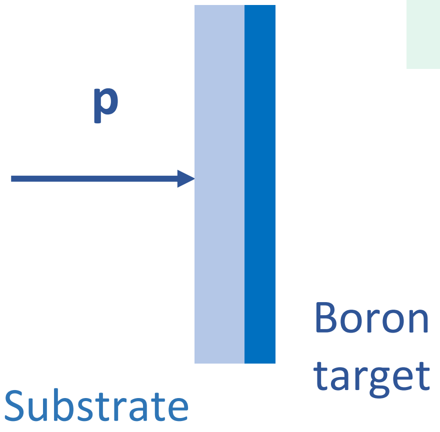


Match the experimental needs

Application: p-^{11}B cross section investigation

Radiation metrology group @ PoliMi

Multiple target generations with incremental **improvements**



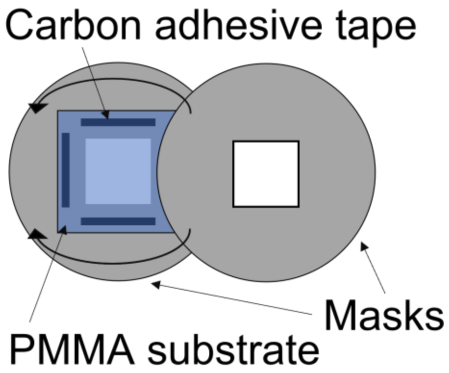
Conventional **proton accelerator**

@ INFN – Laboratori Nazionali di Legnaro

1

First generation

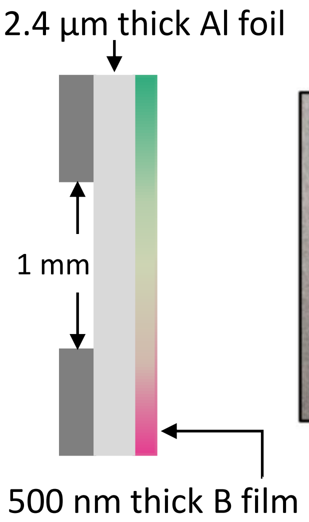
- 1 µm boron film on 50 µm PMMA
- Substrate useful to slow the incoming protons and avoid film stress issue



2

Second generation

- 500 nm boron film on 2.4 µm aluminum foil
- **Well characterized** in thickness, density and composition



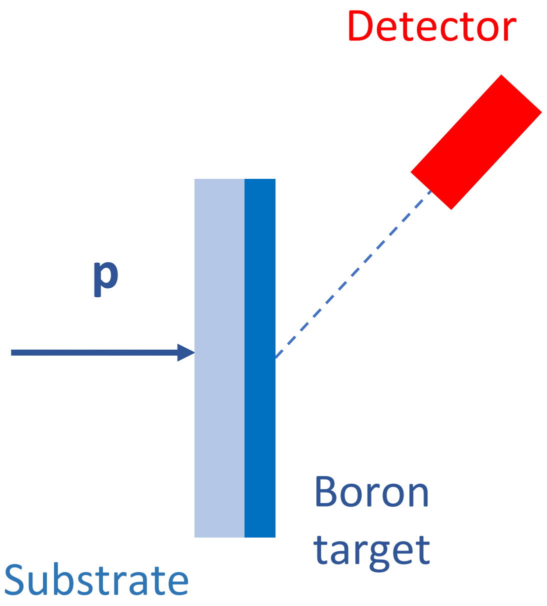
3

Third generation

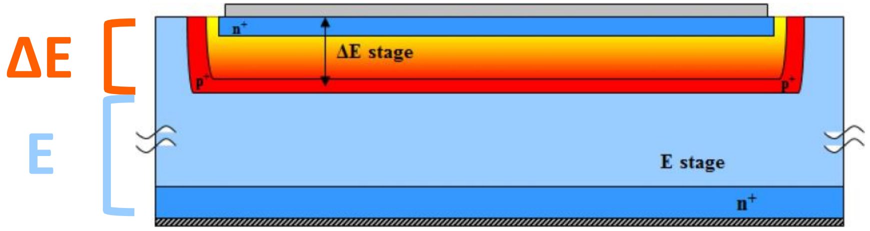
- **Isotopic ^{11}B** films
- Laser cleaning to avoid oxidation
- Analogous film characteristics as previously

Application: p-^{11}B cross section investigation

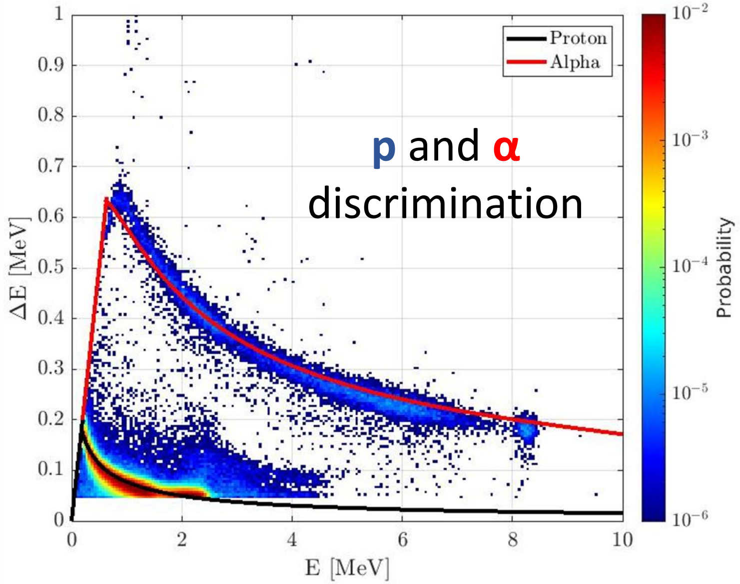
Radiation metrology group @ PoliMi

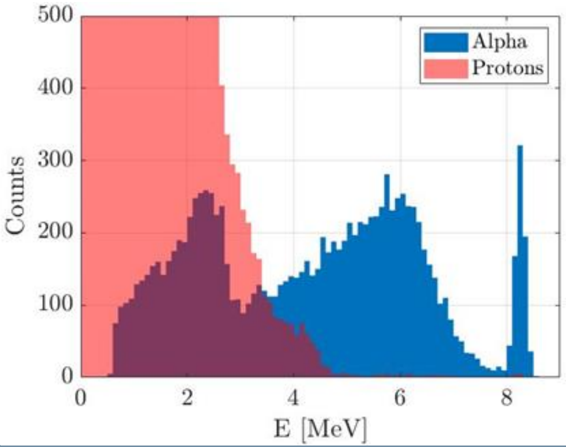


Silicon **telescope detector**



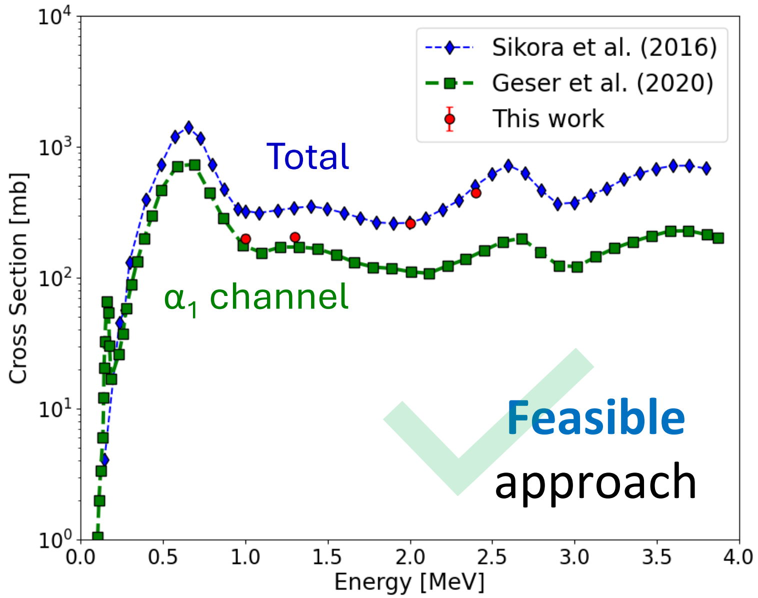
Mazzucconi D. et al., Physica Medica 89, 2021





First generation 1

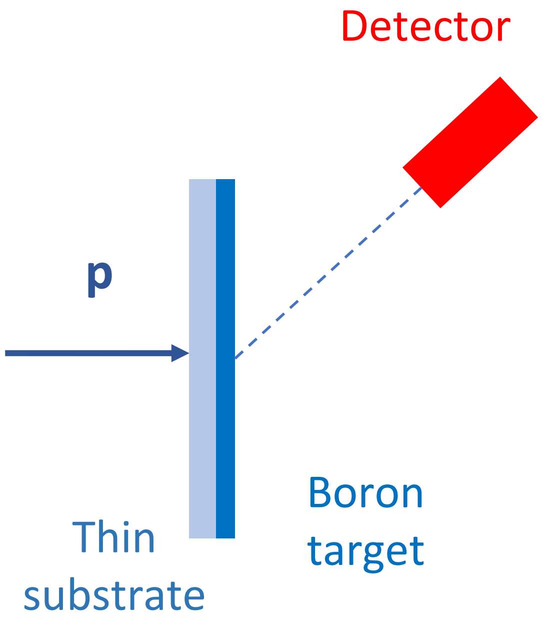
1 µm boron film
on 50 µm PMMA



Feasible approach

Mazzucconi D. et al., Radiation Physics and Chemistry 204, 2023

Application: p-^{11}B cross section investigation



Uncertainties in **target properties** contribute to cross section **error bars**

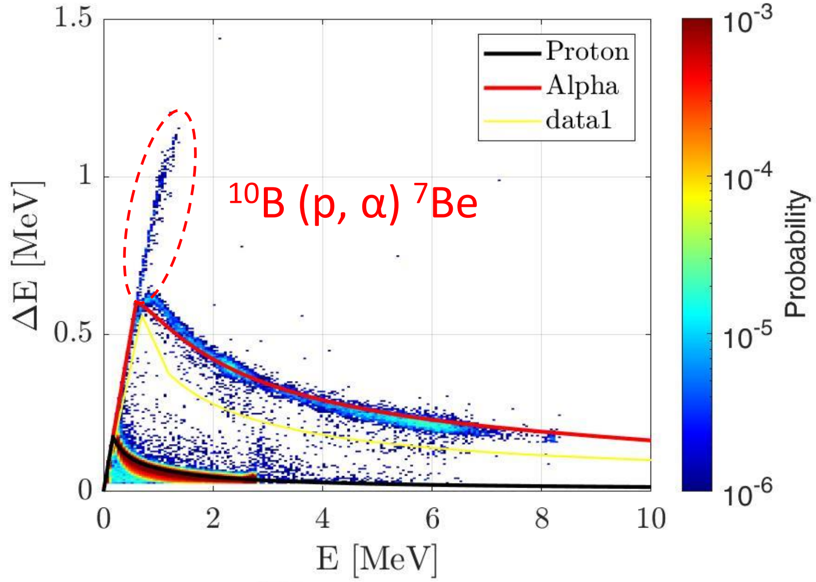
Second generation

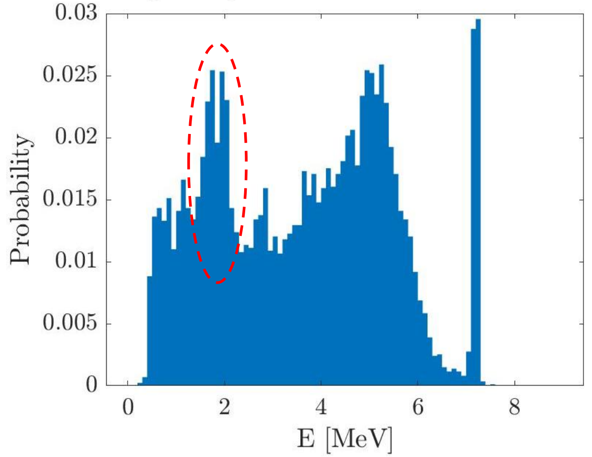
500 nm boron film on 2.4 µm PMMA

Decrease target and substrate **thickness** ⇒ Reduce p and α **attenuation**

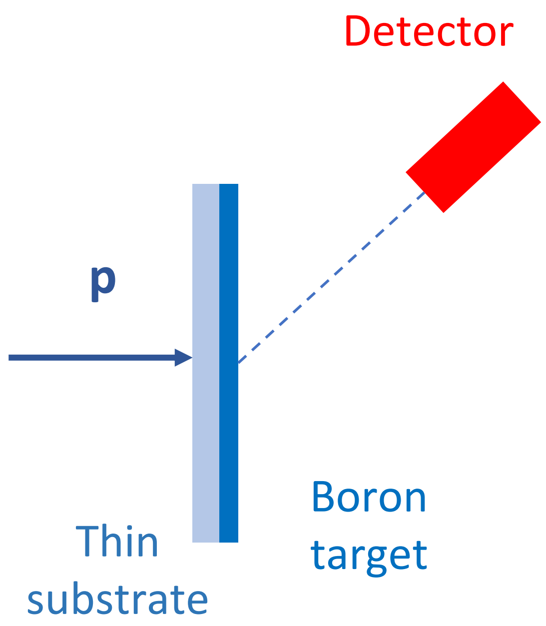
Higher **signal-to-noise** ratio

^{10}B contribution (natural boron)





Application: p-^{11}B cross section investigation



Uncertainties in **target properties** contribute to cross section **error bars**

Decrease target and substrate **thickness** ⇒ Reduce p and α **attenuation**

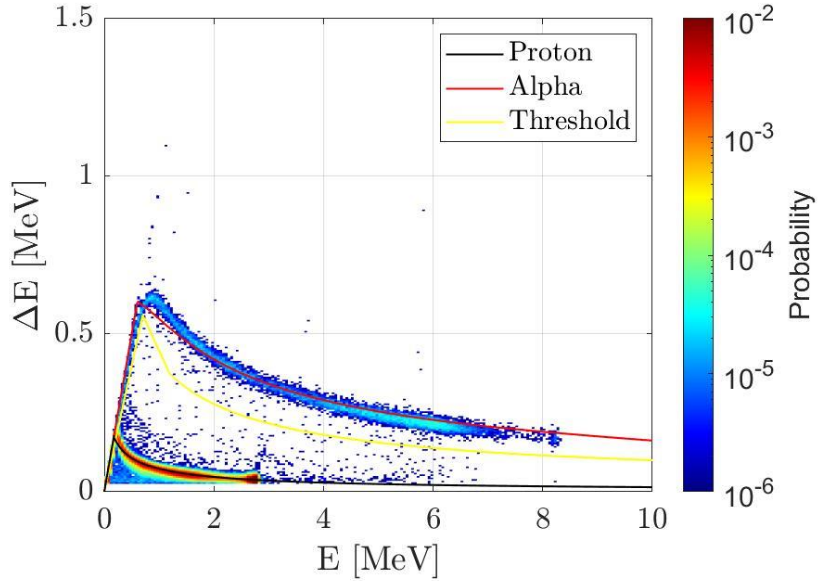
3

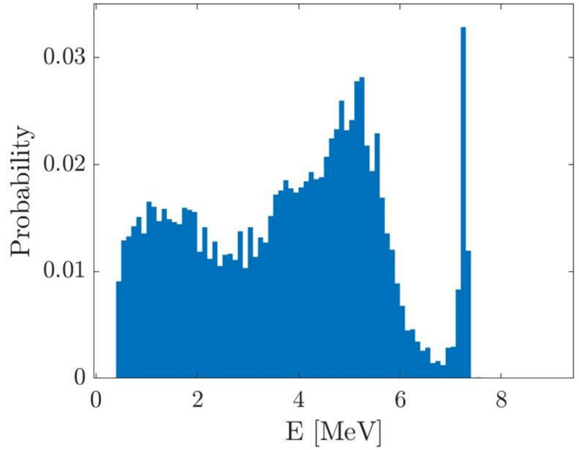
Third generation

^{11}B isotopic boron target

Refined cross section data in the **0.3-3 MeV** range

Data analysis in progress





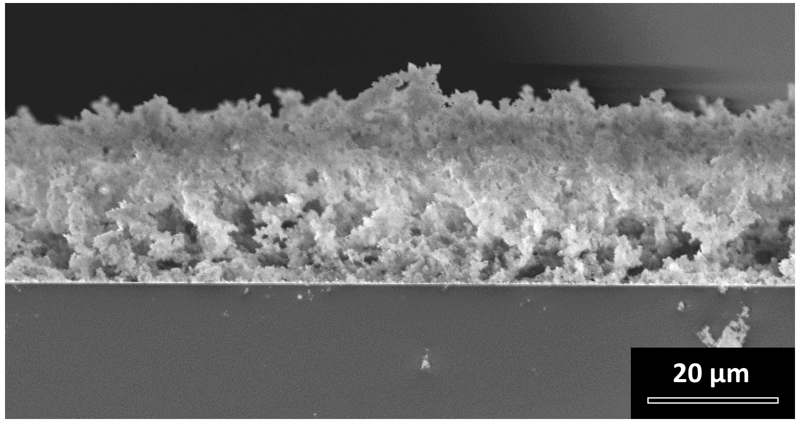
Low density boron nanofoams with fs-PLD

Relative **slowing efficiency** of the background gas

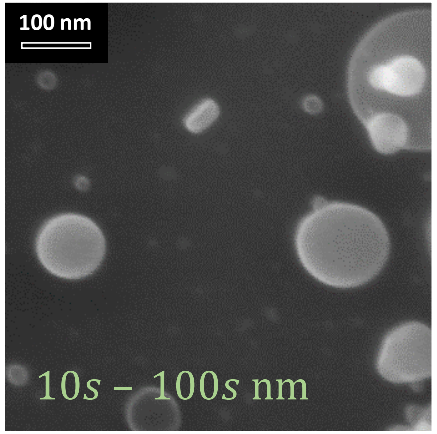
Dimensions, **energetics** and **concentration** of the ablated species

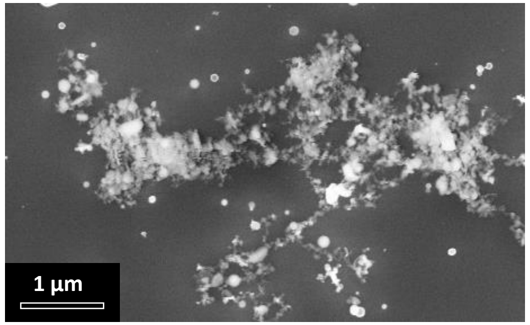
Material properties

- Density
- Thickness
- Uniformity



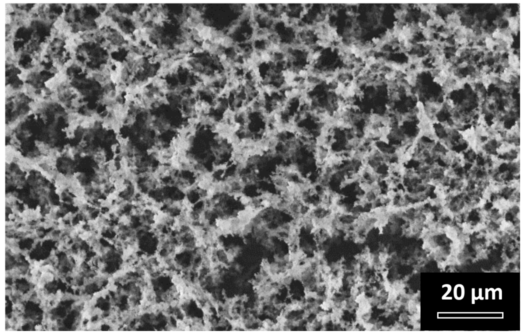
1 Direct **nanoparticle** production





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

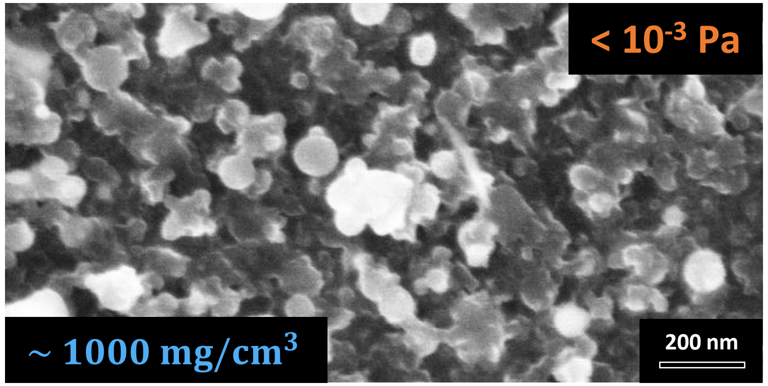
3 **Deposition** on the substrate and foam growth

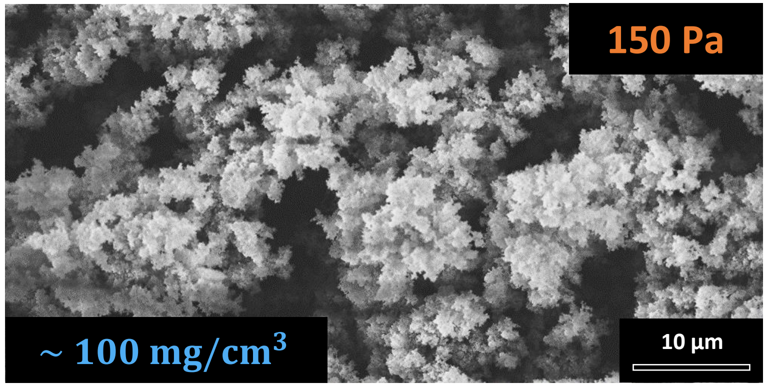


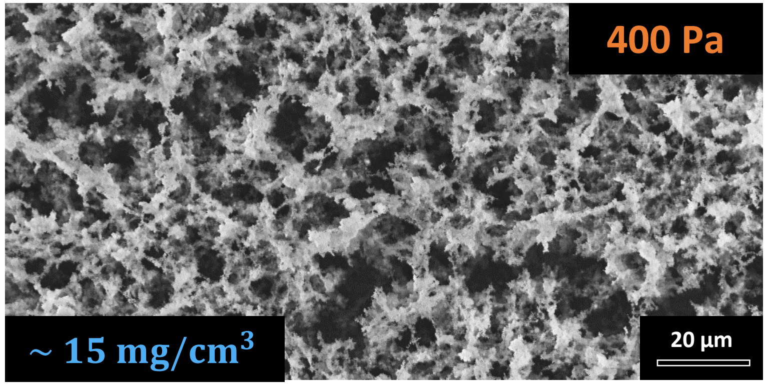
Low density boron nanofoams with fs-PLD

All are nanostructured films

Argon gas **pressure** →







← **Density**

Deposition parameters:

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

⇨

Film properties:

- Tunable density, down to $\sim 15\ \mathrm{mg/cm^3}$
- $10\ \mu\mathrm{m} - \sim 100\ \mu\mathrm{m}$ thickness
- $\sim 2\%$ Mg impurities and $\sim 20\%$ oxygen content
- Uniformity scale of $\sim 10\ \mu\mathrm{m}$

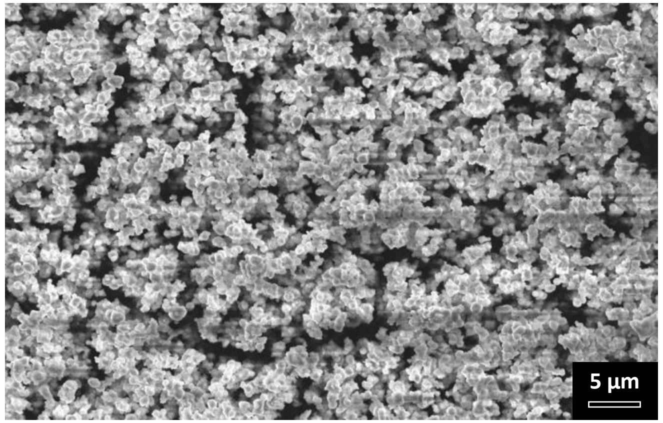
Freedom in **material choice**

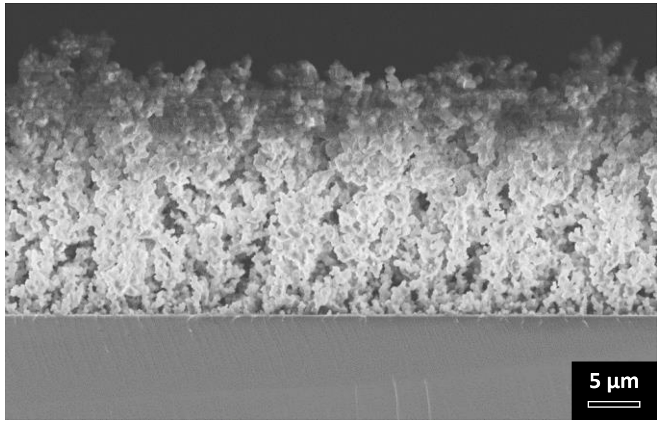
⇩

Hydrogen enrichment

Polymeric nanostructured films with fs-PLD

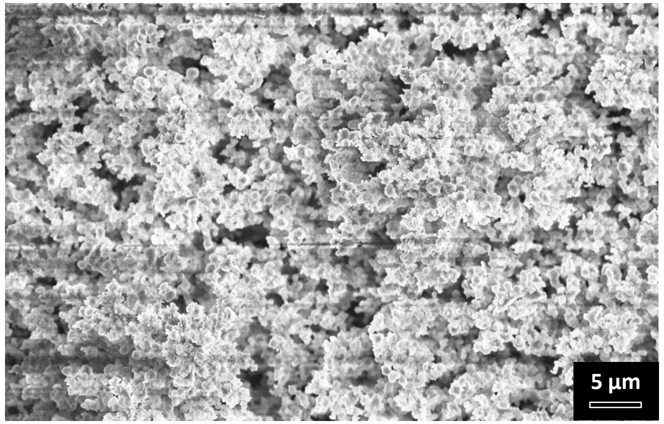
CH
Substrate

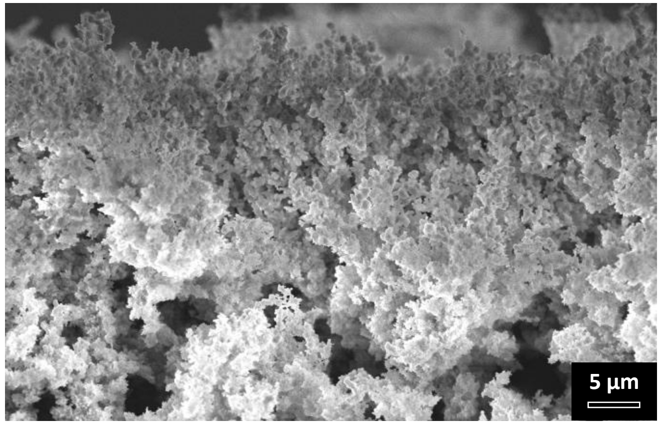




Especially challenging

- PMMA, PP, **HDPE**
- Lacking thickness uniformity
- Contamination of the optical elements in the PLD
- Compact **nanoparticle-assembled** film even at high pressure (5000 Pa Ar)





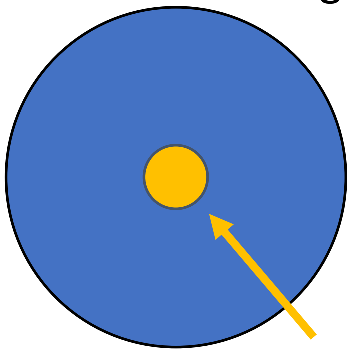
CH
B
Substrate

Time consuming

Fully exploit the **versatility** of **fs-PLD**

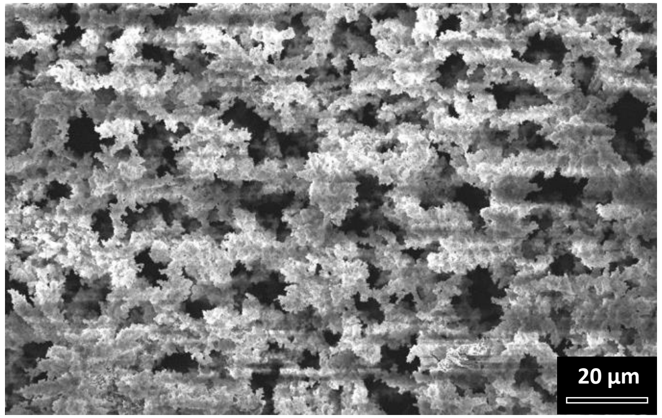
B & CH codeposited nanofoams

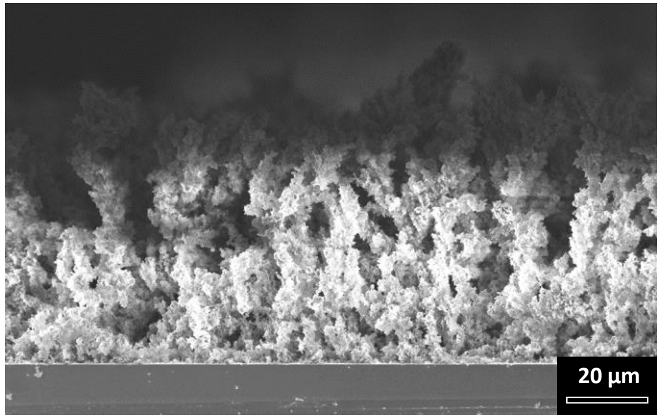
Still challenging



Different **fluence-pressure conditions** needed → **Average** conditions (depending on requirements)

Different **ablation plume** orientation → Inhomogeneous **CH enrichment** → Mitigation through **target movement**





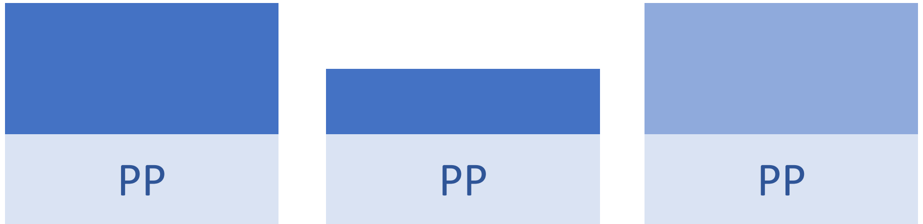
Material properties:

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

Targets for p-^{11}B fusion campaign

B foam

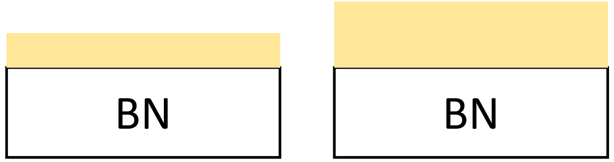
10-15% O, 1% Mg



100 mg/cm^3	100 mg/cm^3	50 mg/cm^3
100 µm	50 µm	100 µm

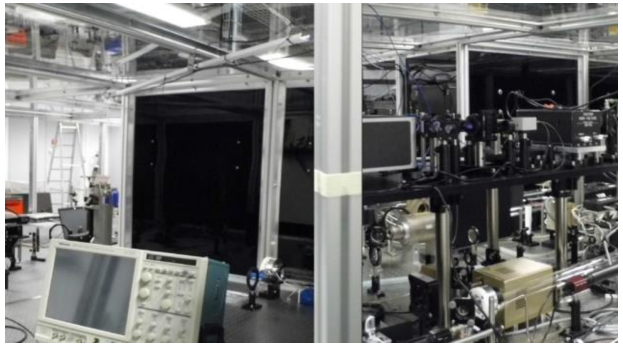
CH foam on BN substrate

- HDPE
- 120 mg/cm^3
- 10-20 µm



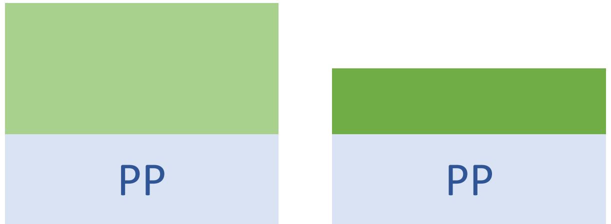
- 8 J pulse energy
- 800 fs
- λ 1054 nm
- ~ 10^{19} W/cm^2

@ QUB, Taranis laser



B + CH foam

41% H, 27% B, 21% C,
10% O, 1% Mg



40 mg/cm^3	80 mg/cm^3
100 µm	60 µm

Ongoing data analysis

⇩

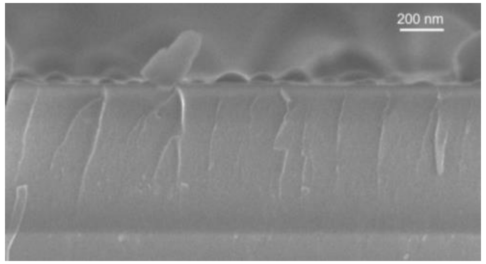
In-foam fusion reactions

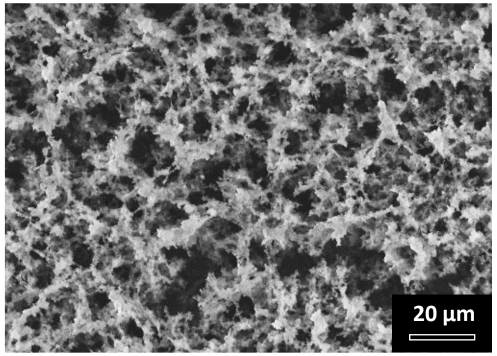
Conclusions and perspectives

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

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

Tailored targets for specific **applications**





Boron **equation of state** study

Conclude both ongoing **data analyses**

Leverage the **experience** on **boron-based films** production

Boron coatings for **Tokamaks** in **MCF**

Investigate p-^{11}B in **different laser systems** (i.e. compact)

FUSION project

Thank you for your attention!