

Advanced carbon based targets for laser-plasma experiments



- Activities performed within the framework of a collaboration between:

- Our group from



POLITECNICO
MILANO 1863



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D. Dellasega



V. Russo



K. Ambrogioni



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D. Vavassori



D. Orecchia



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- The  **eli Beamlines** team



L. Giuffrida



D. Margarone



F. Schillaci



A. Velyhan



M. Tryus



F. Grepl



V. Kantarelou



M. Žáková

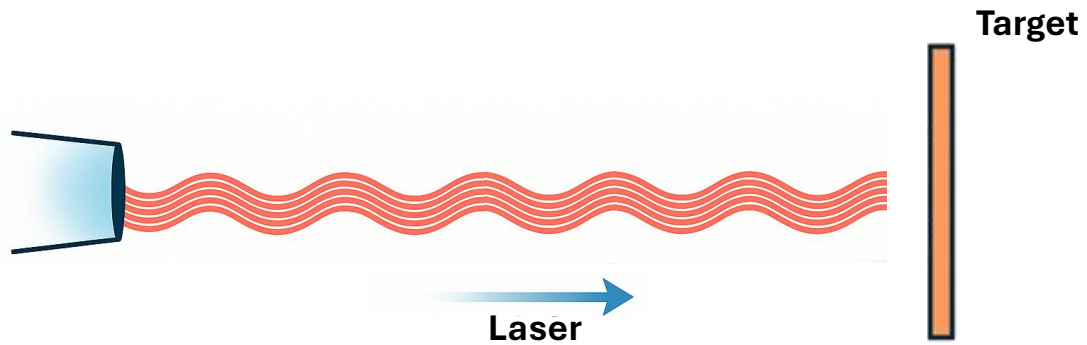


T. Chagovets



N. Gamaionova

Laser-Matter Interaction



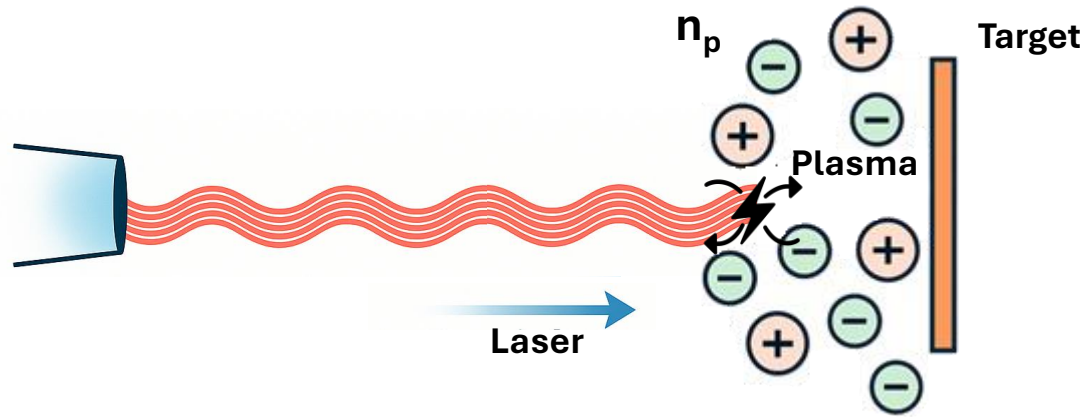
Laser

- Intensity ($I > 10^{13} \text{ W/cm}^2$)
- Duration ($\text{fs} - \text{ns}$)
- Wavelength
- Energy ($\text{mJ} - \text{MJ}$)
- Repetition Rate

Target

- Density
- Thickness
- Composition

Laser-Matter Interaction



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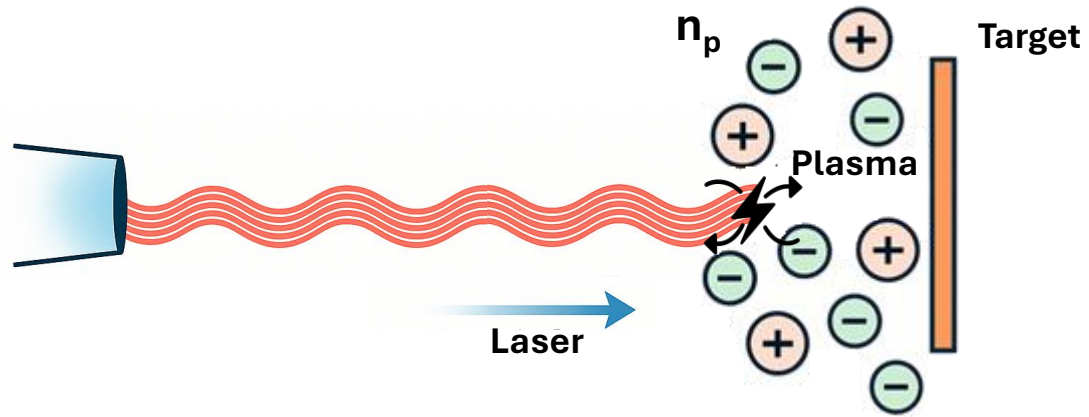
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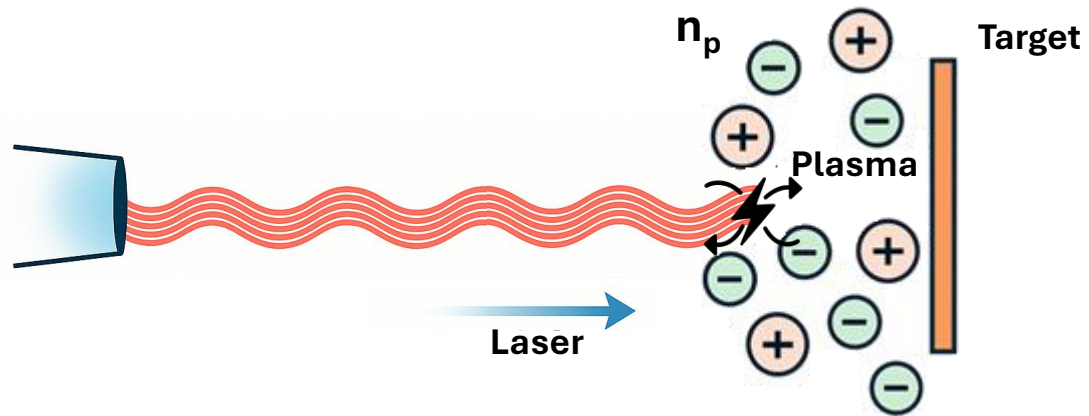
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Regimes of interaction depending on plasma density (n_p)
with respect to the **critical density** (n_c)

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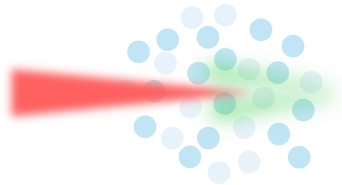
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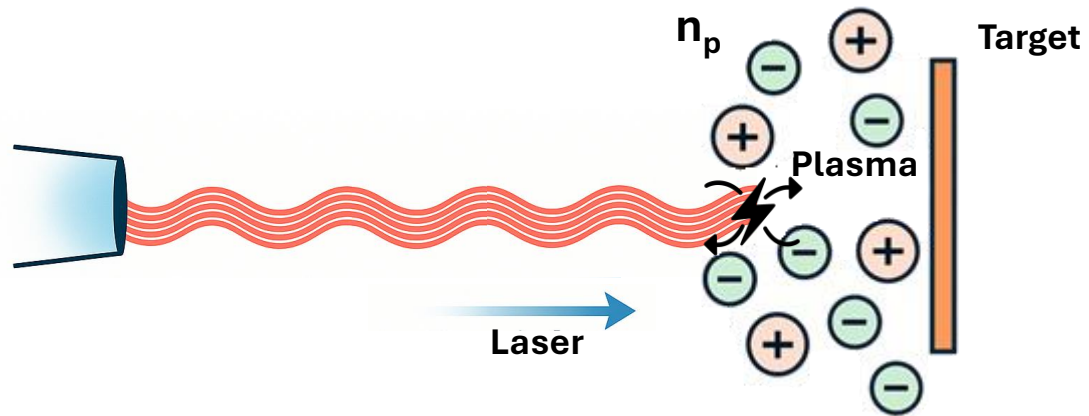
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$$n_p < n_c$$



Laser propagation

Laser-Matter Interaction



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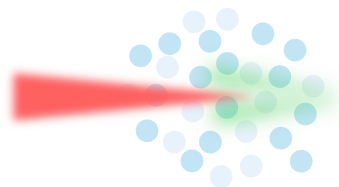
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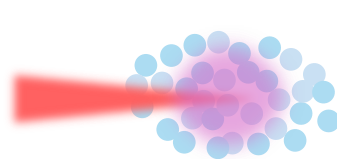
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Near-critical

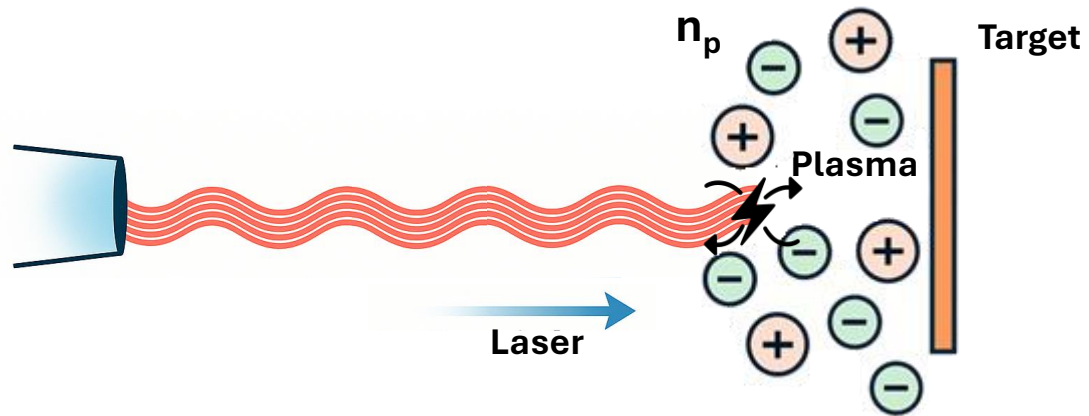
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Laser propagation

Enhanced absorption

Laser-Matter Interaction



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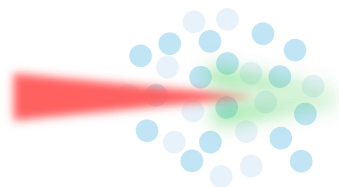
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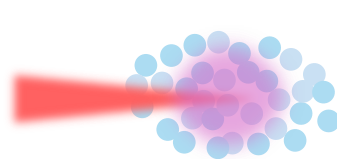
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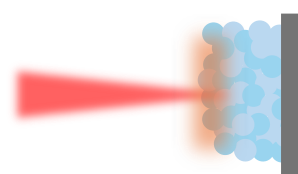
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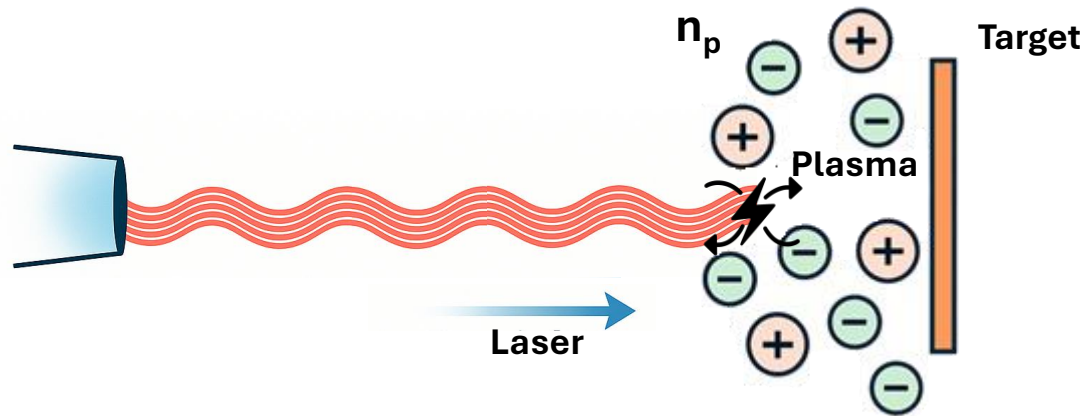
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Surface interaction

Laser-Matter Interaction



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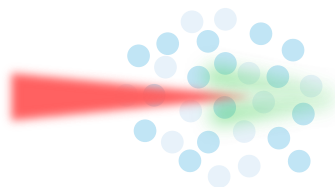
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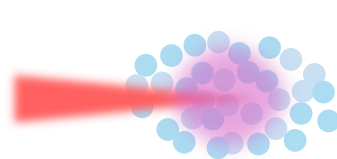
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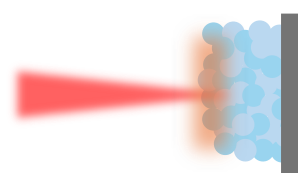
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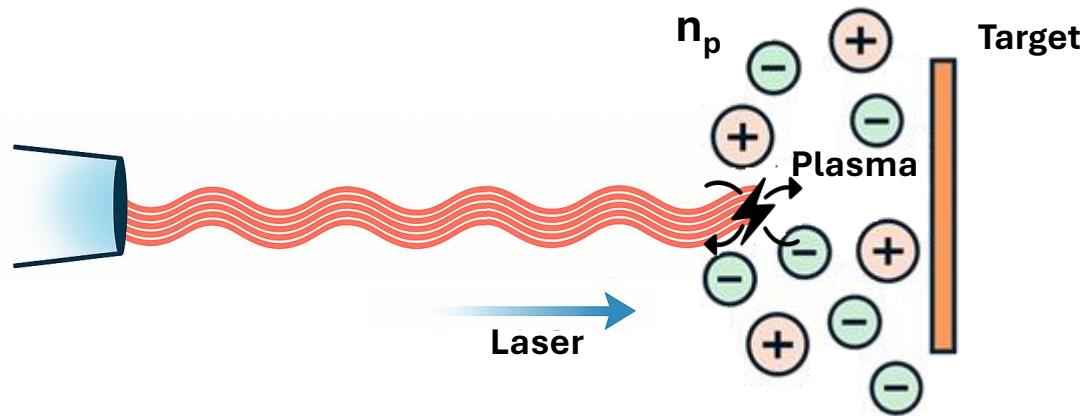


Surface interaction

Possible applications

- Laser driven ion acceleration
- Laser driven electron acceleration
- Ultra-fast gamma generation
- Inertial confinement fusion
- Proton-Boron fusion
- Warm dense matter study
- Radioisotopes production

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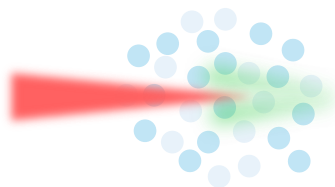
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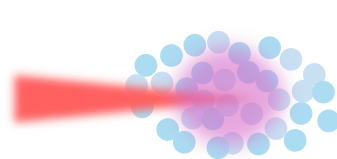
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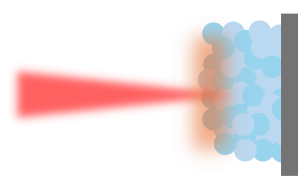
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Enhanced absorption

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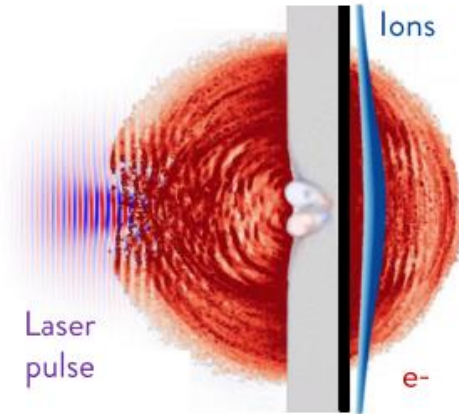
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Acceleration regimes and target strategies

TNSA



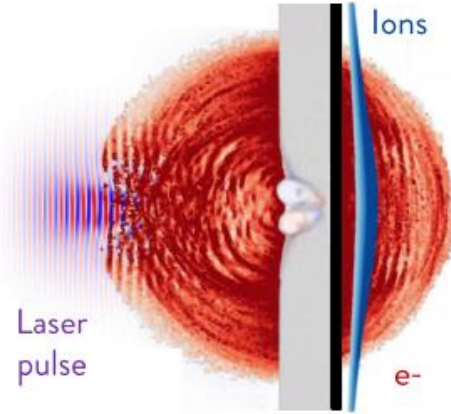
Enhanced absorption

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Acceleration regimes and target strategies

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- PLD produced Nanofoam based **Double Layer Targets**
- Near-critical coating to **enhance laser absorption**



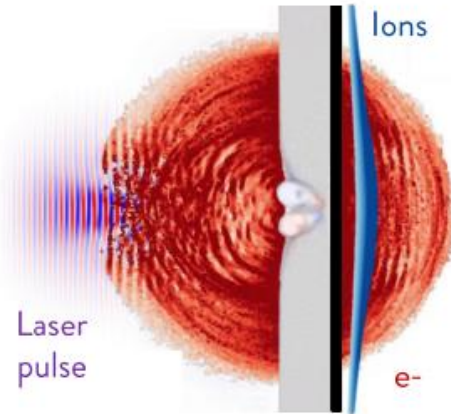
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Tomorrow 11:10 A. Maffini - *Tailoring laser-matter interaction using near-critical nanofoam targets*

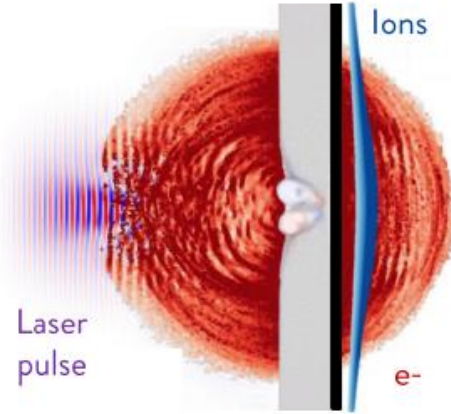
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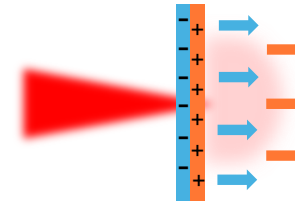
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RPA



Enhanced absorption

Controlled areal density

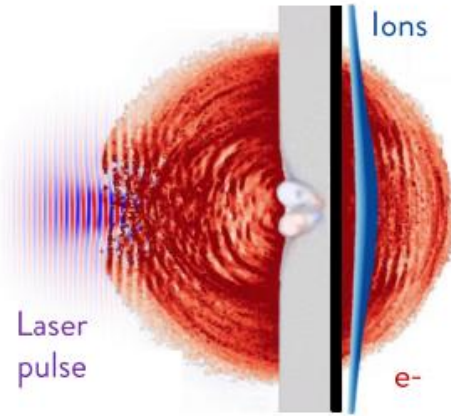
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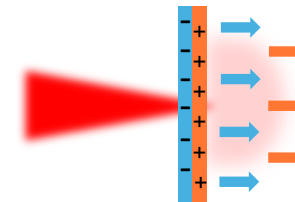


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RPA

- **Ultrathin solid foils** required for efficient RPA
- **Areal density** is a key parameter

 $\sigma = \rho \cdot d$  Radiation Pressure coupling



Enhanced absorption

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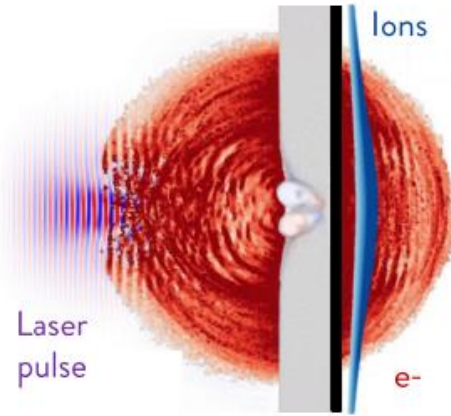
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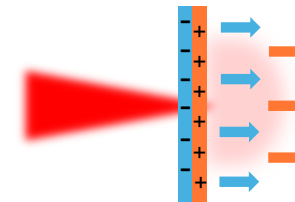


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The challenge:
Achieving ultralow areal density while preserving target integrity

Enhanced absorption

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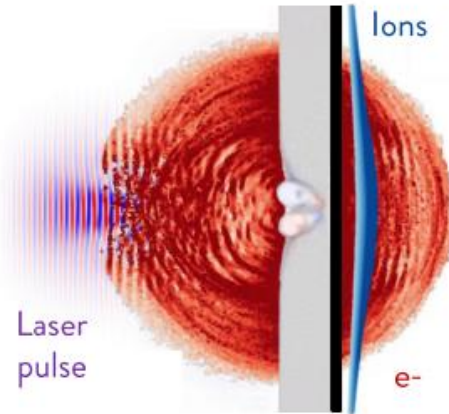
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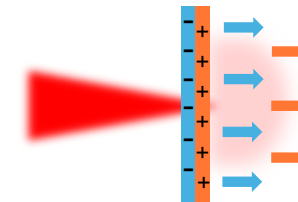


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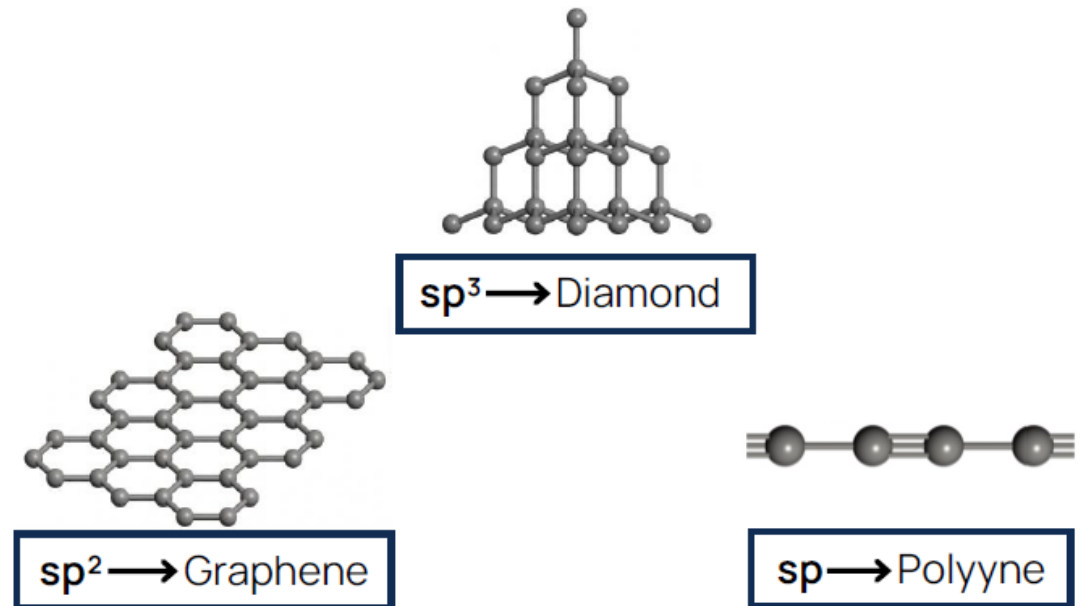
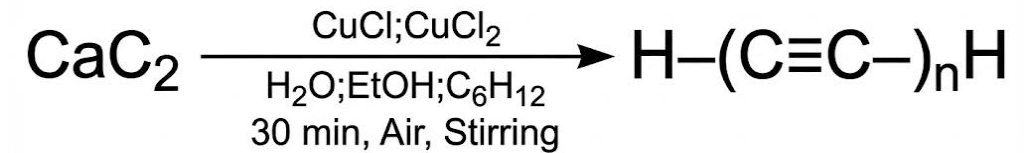
Novel chemical synthesis of ultrathin carbon membranes via polyyne-solution evaporation

Controlled areal density

RPA

A novel approach – From Polyynes to C membranes

What are polyynes?



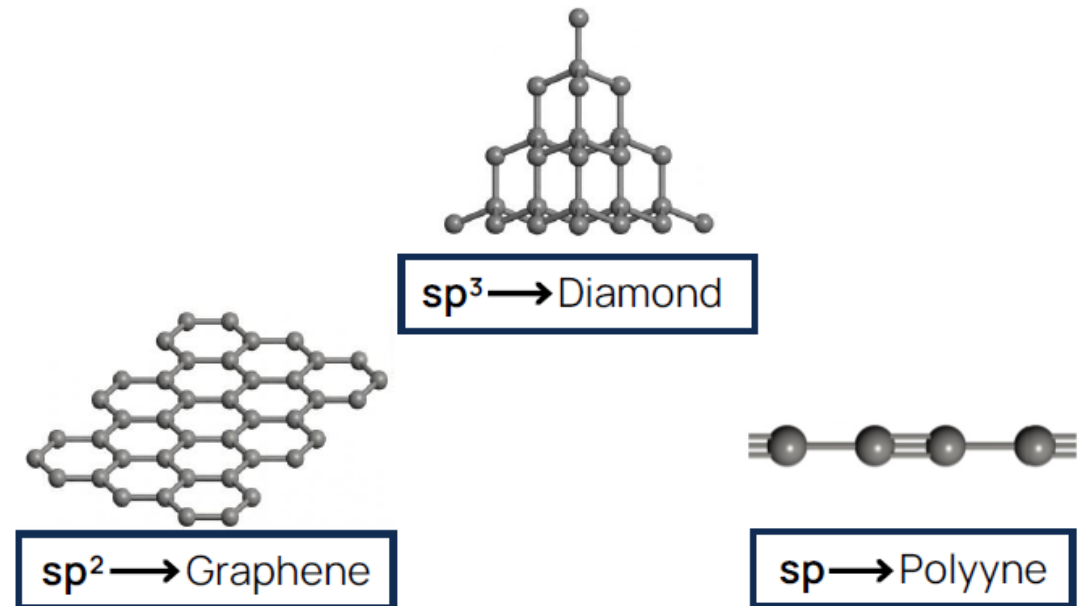
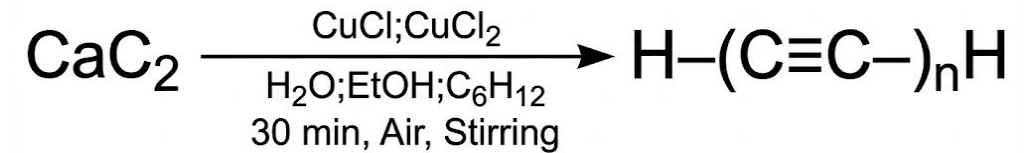
F. Cataldo, Carbon 43.13, 2792 (2005).

M. Agozzino et al., J. Phys. Chem. C, 2026.

A novel approach – From Polyynes to C membranes

What are polyynes?

- sp-Hybridized **carbon linear chains**
- **Chemically synthesized** in cyclohexane solution

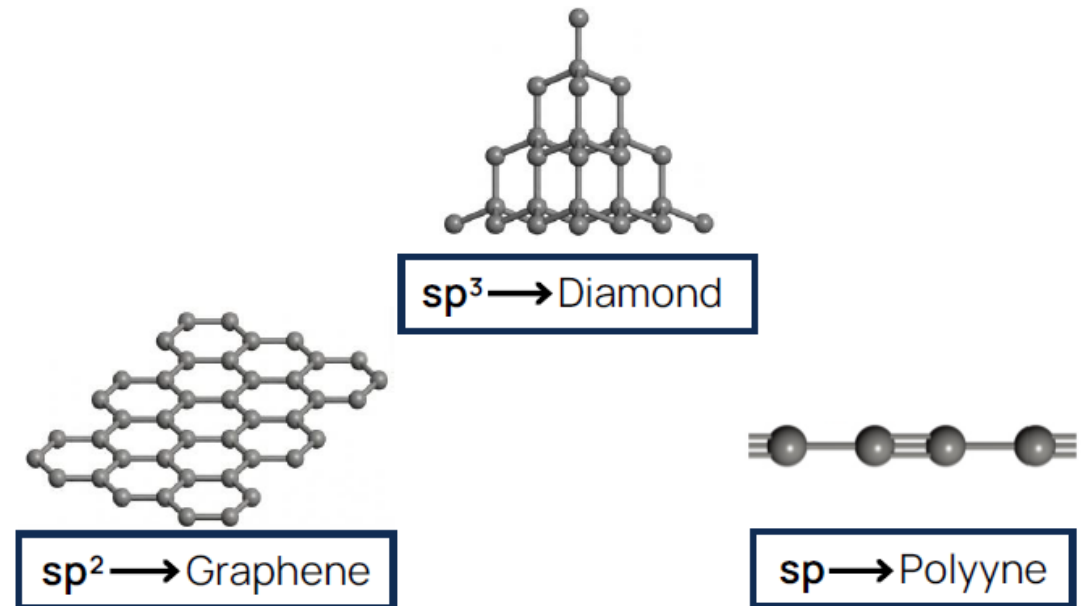
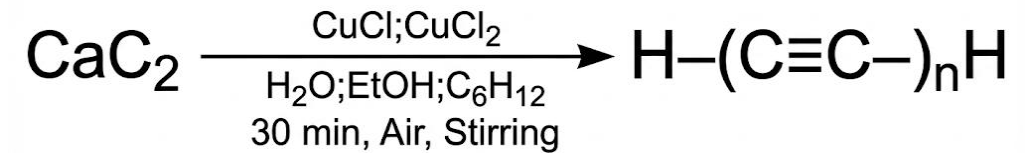


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Stable sp component also after evaporation!!

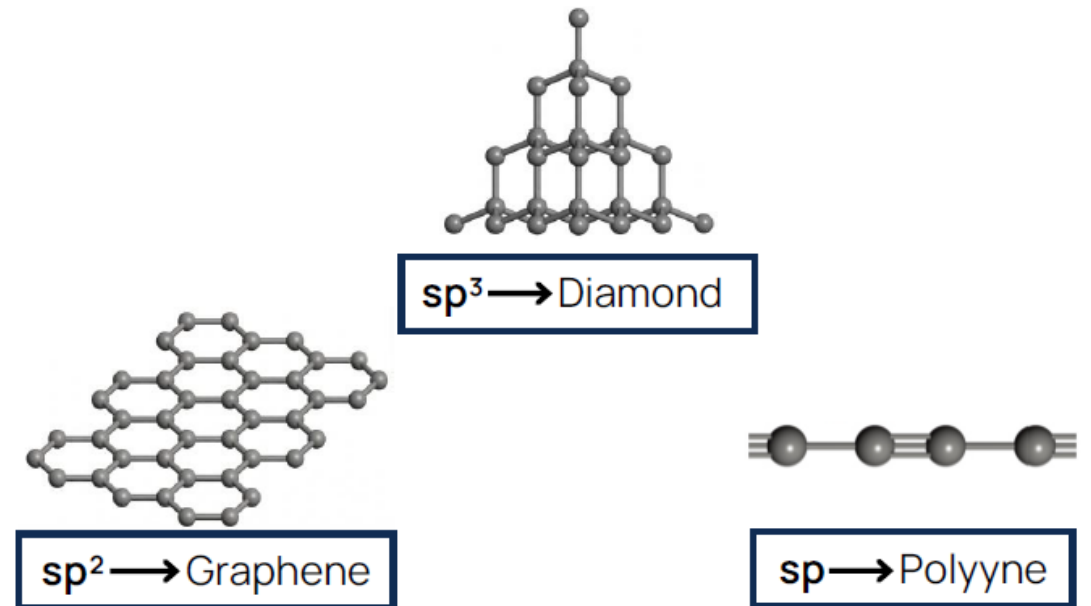
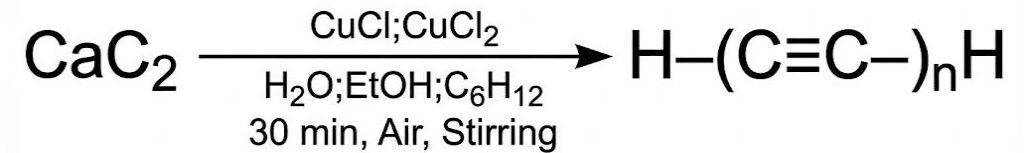
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- Expected **high mechanical robustness** and **high Hydrogen content**

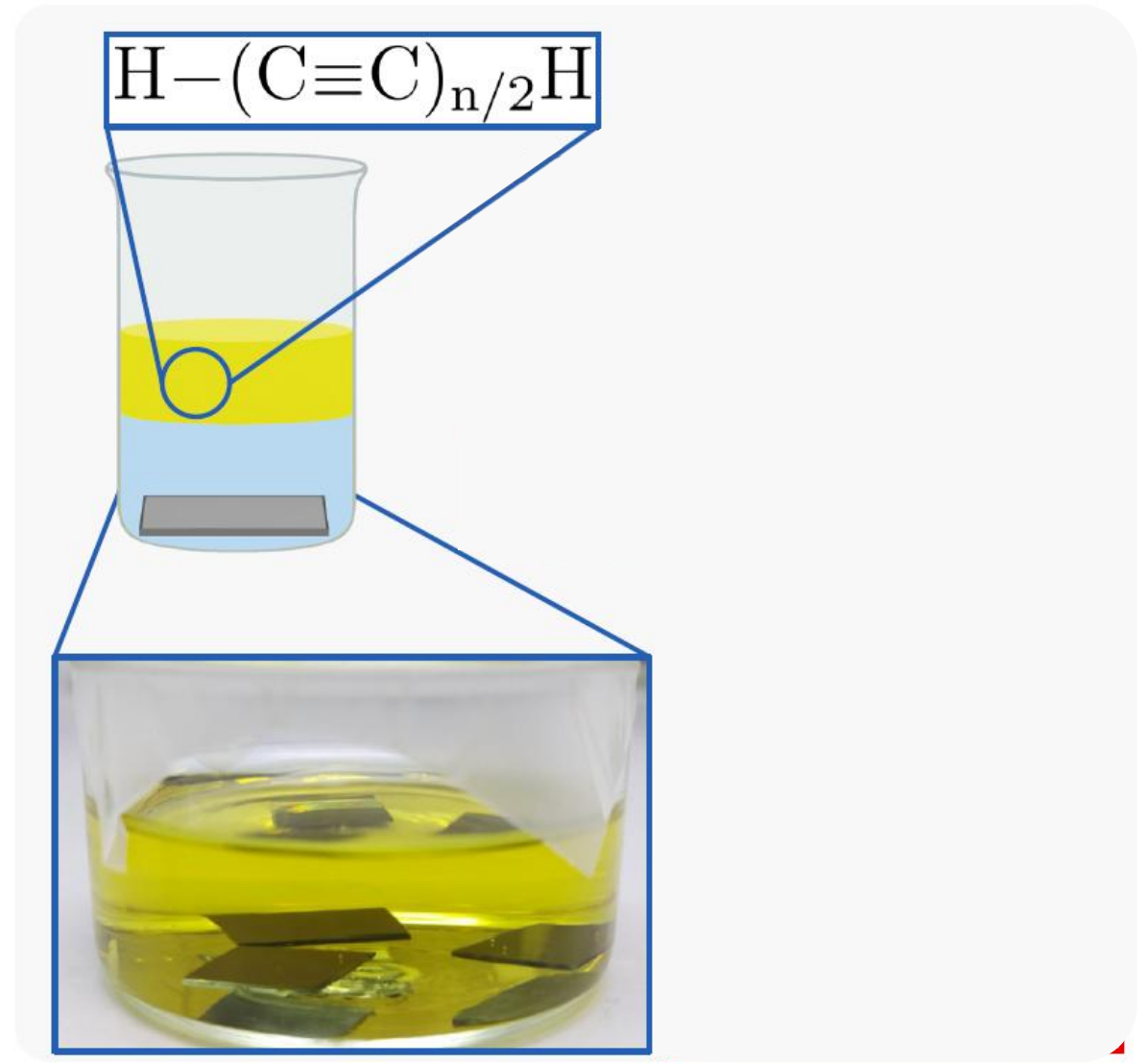
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Carbon membrane synthesis

1) **Synthesis of polyynes** solution in cyclohexane

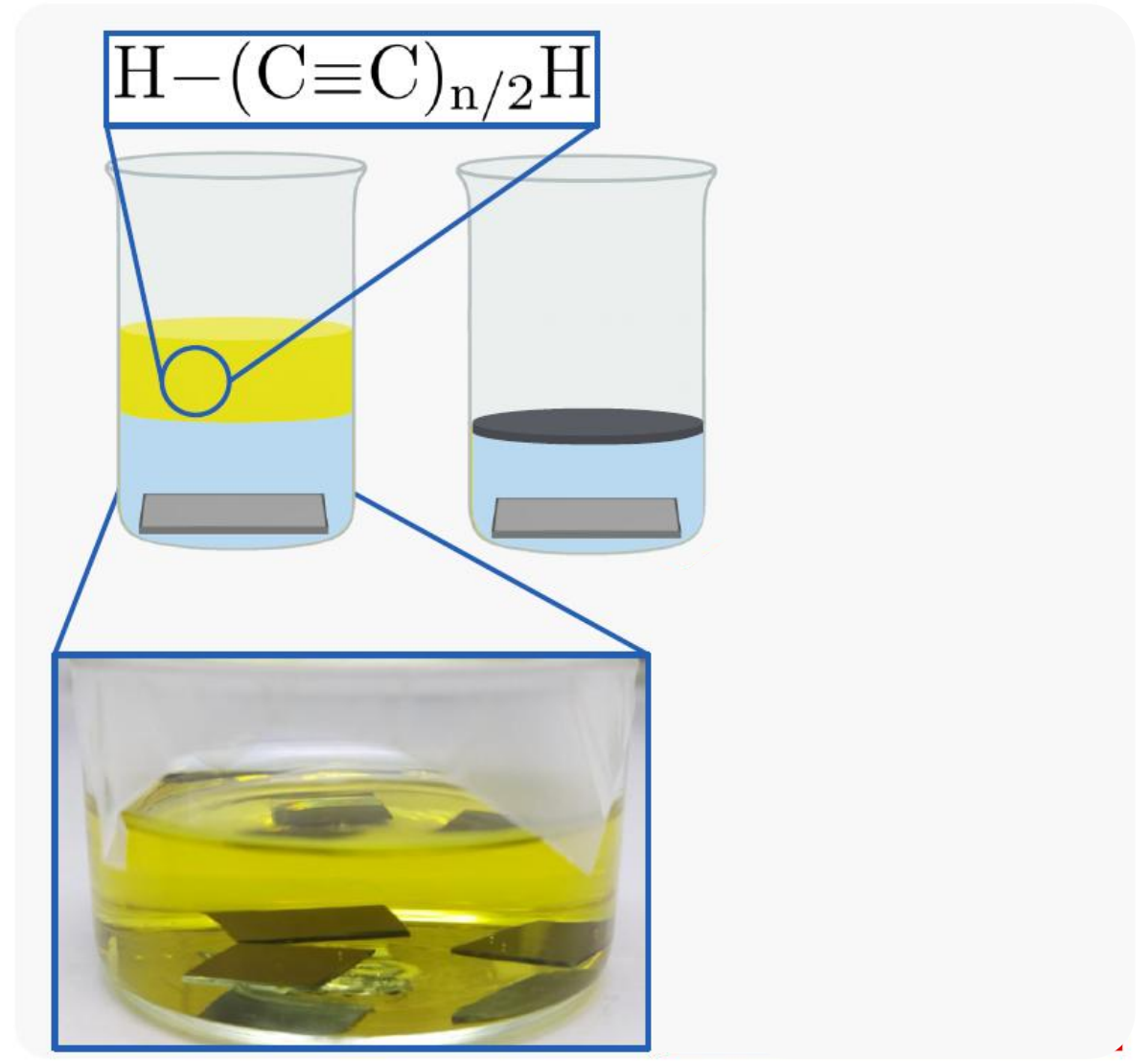


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- 2) **Evaporation** of the solution at water interface
- 3) Membrane **formation**

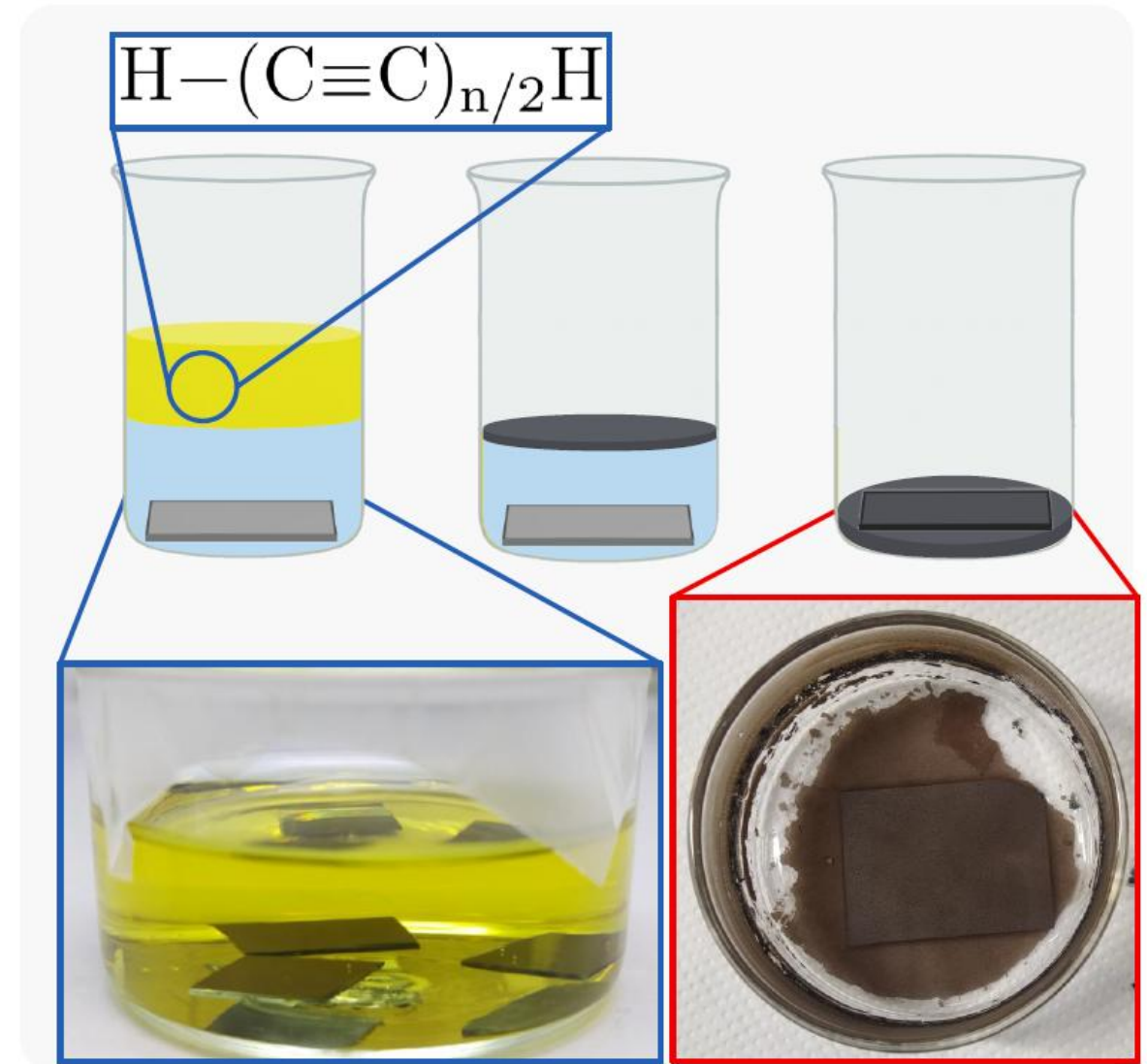


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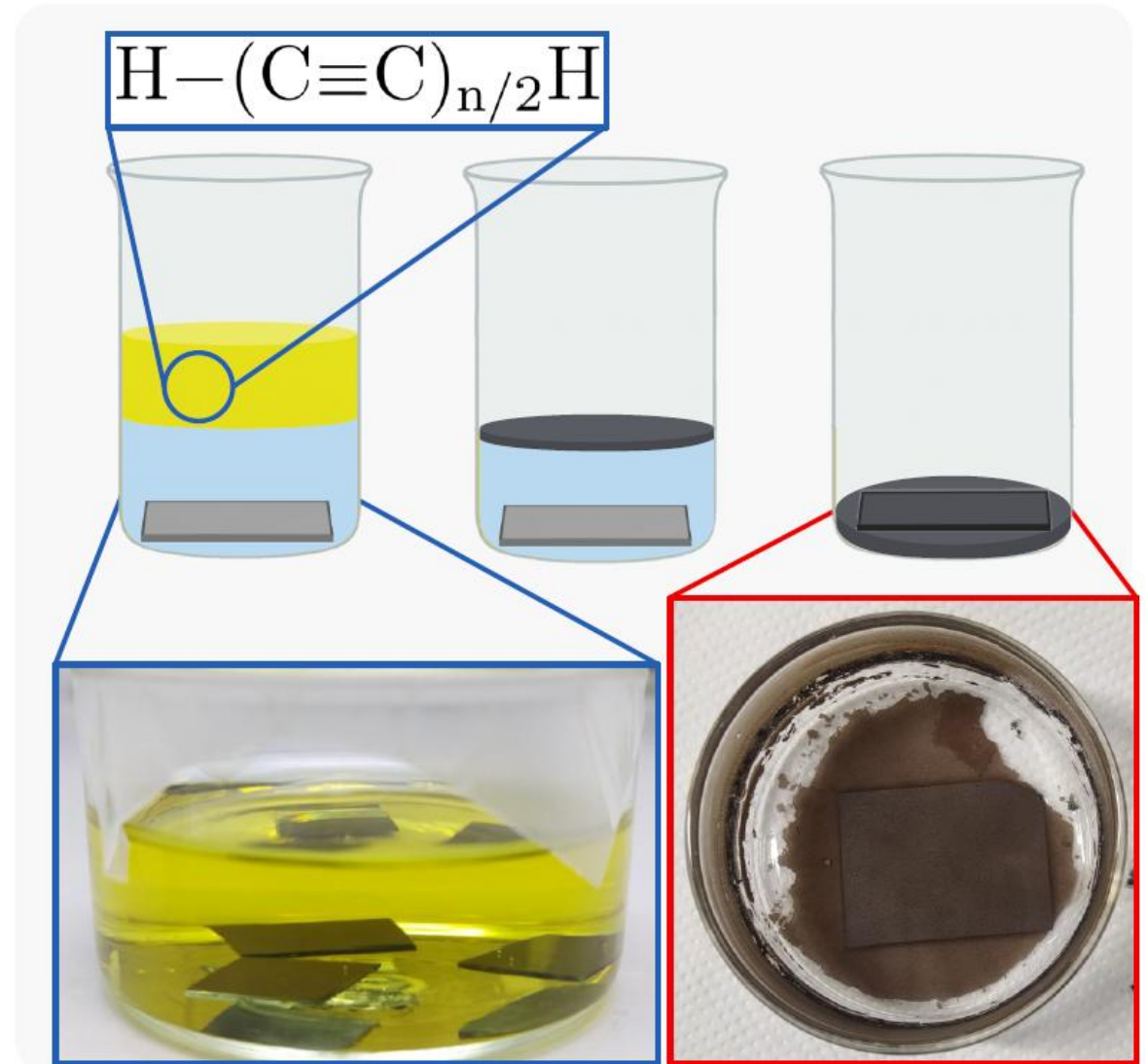
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Variable parameters

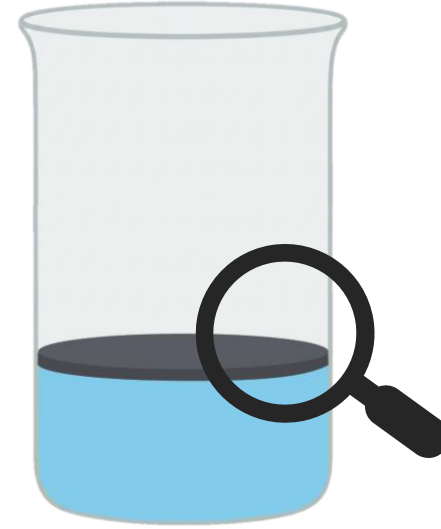
- Initial concentration (C_0)
- Polyynes areal density ($\#Py/A$)
- Evaporation time



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Carbon membrane features



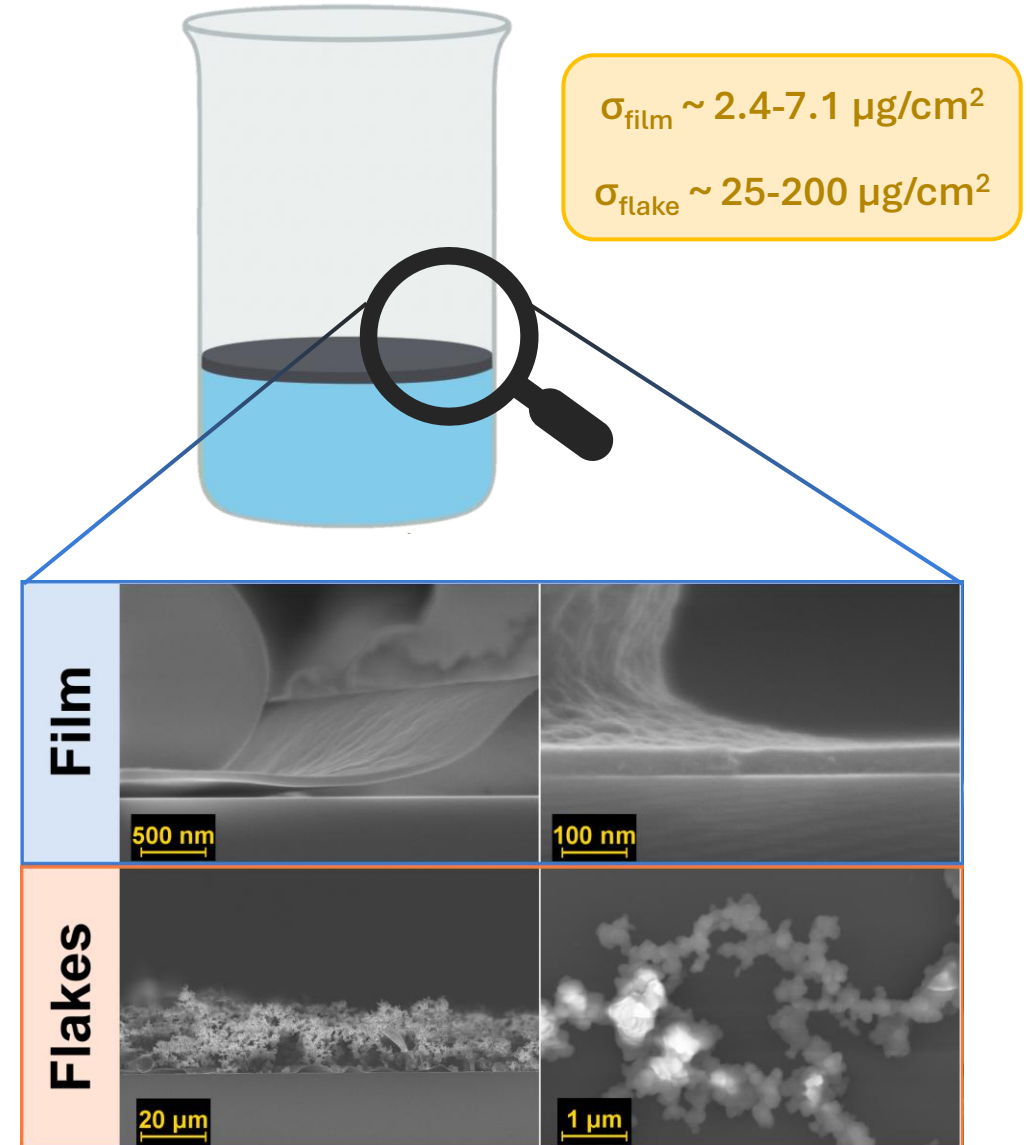
Carbon membrane features

Compact Nanometric Carbon Film

Ultrathin → **20-60 nm** thickness
Half of Carbon bulk density → **1.19 g/cm³**

Nanostructured Carbon Flakes

Micrometric thickness → **10-80 μm**
Ultra low density → **24.7 mg/cm³** ($\sim 4 n_c$)



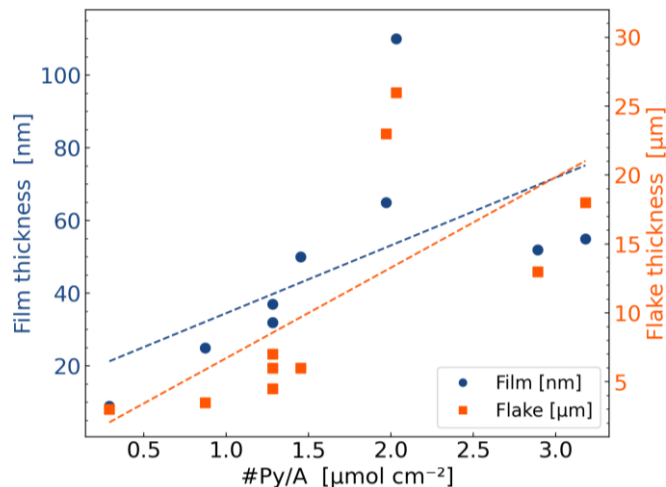
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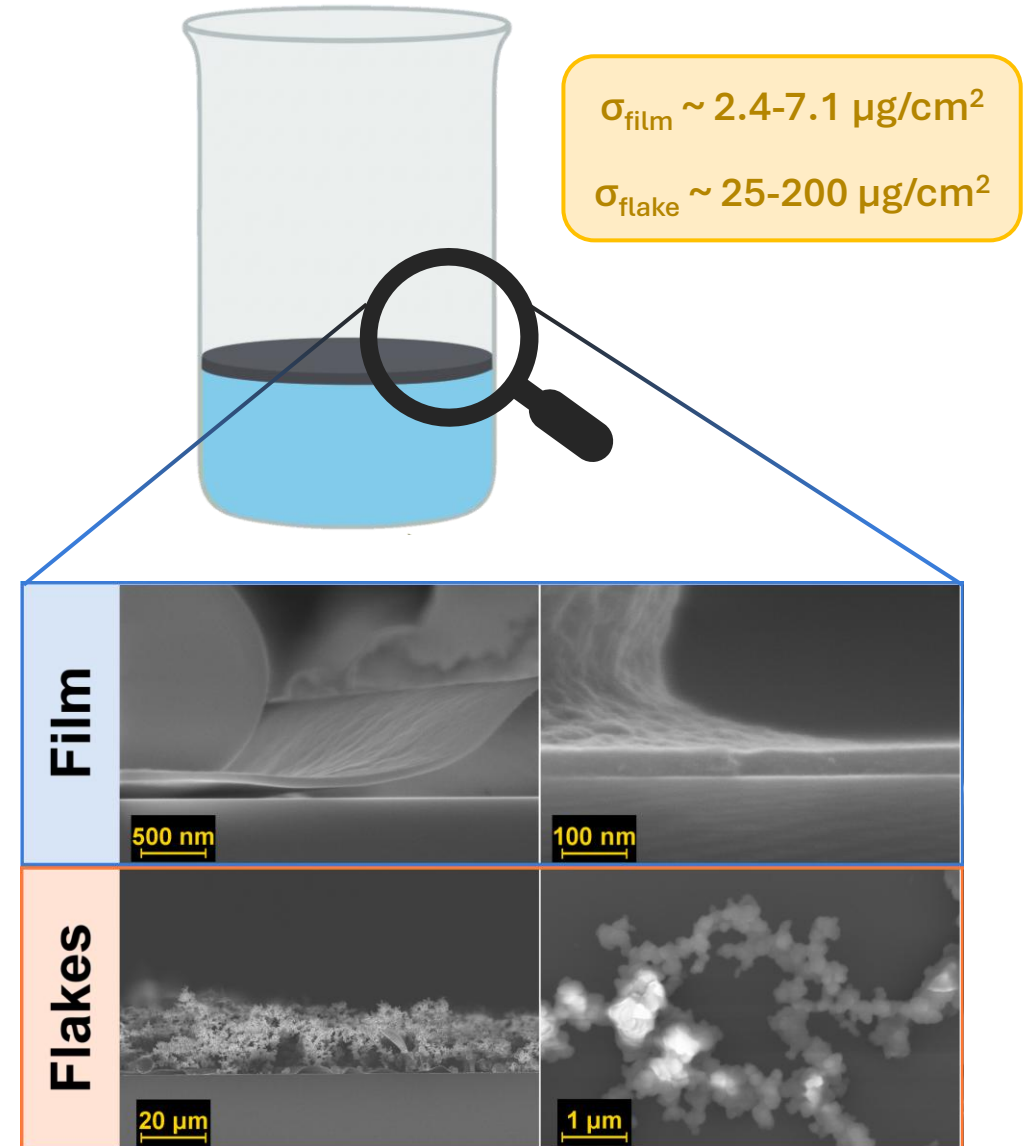
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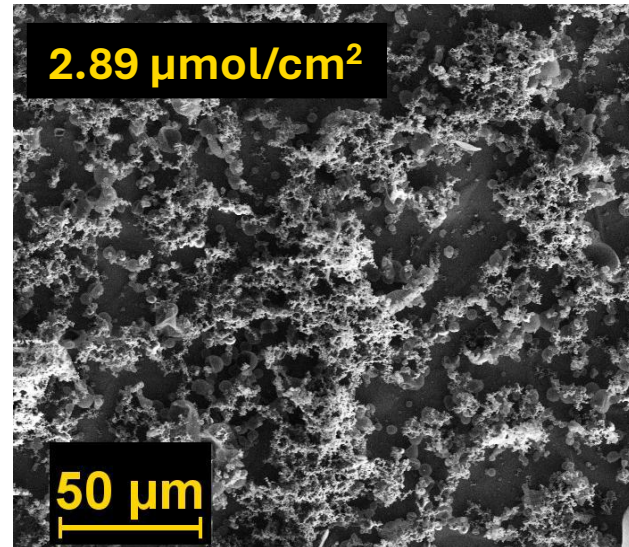
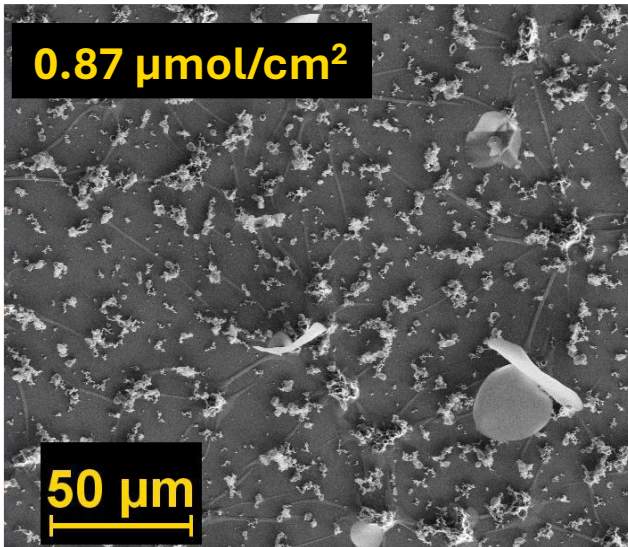


≡≡≡ Polyyne areal density
↓
≡≡≡ Features thicknesses



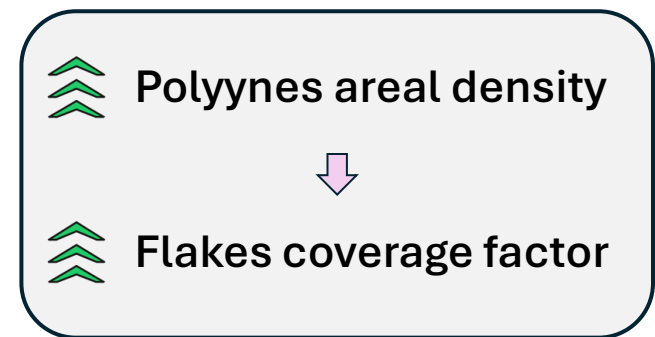
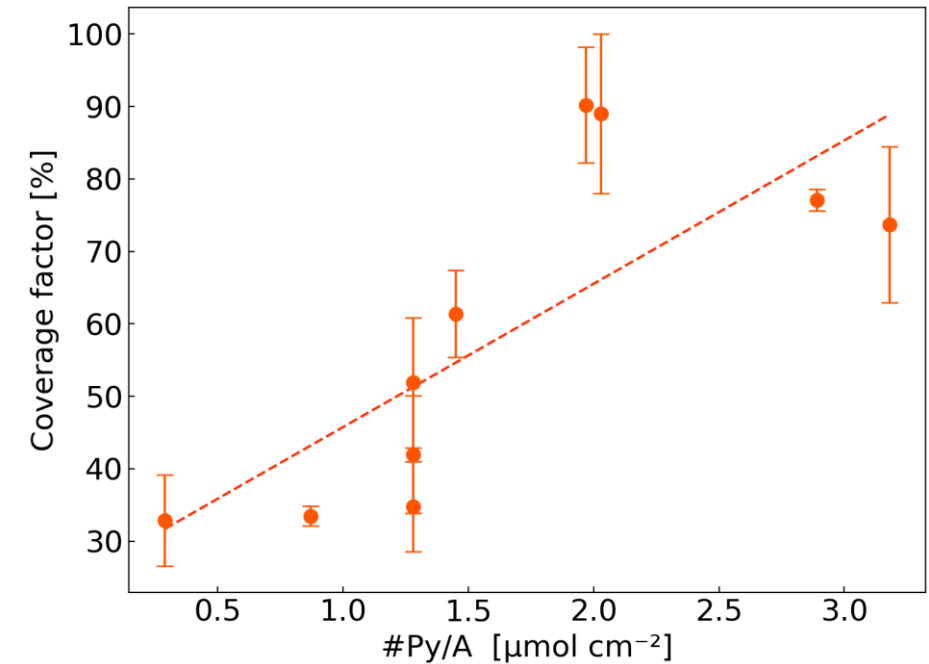
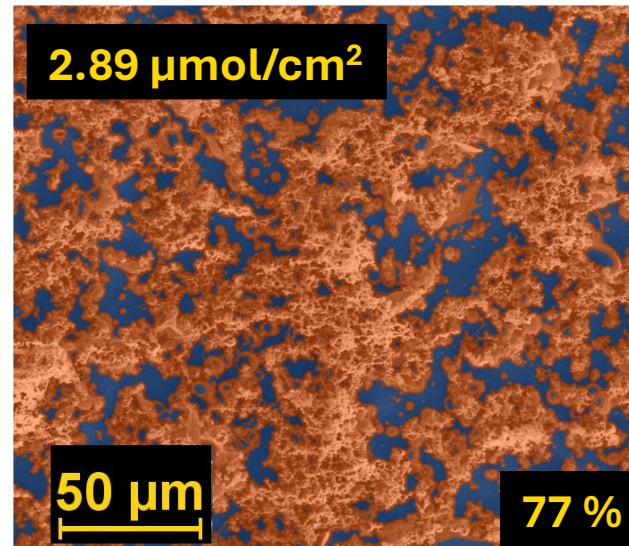
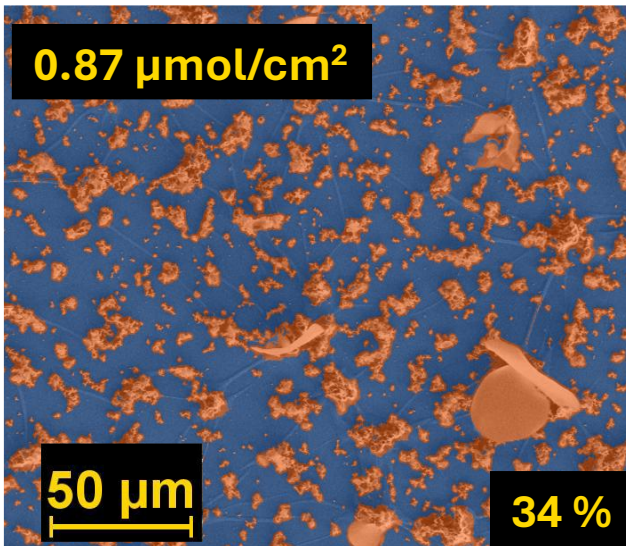
Carbon flake coverage factor

- Coverage factor (CF) quantified from **SEM images** analysis



Carbon flake coverage factor

- Coverage factor (CF) quantified from **SEM images** analysis
- **Higher Polyynes** areal density promotes **more interconnected flake network**
- CF ranging from **30 %** to **90 %**



Morphology & evaporation stages investigation

Production variables

- Polynes concentration (#Py)
- Time at the water interface

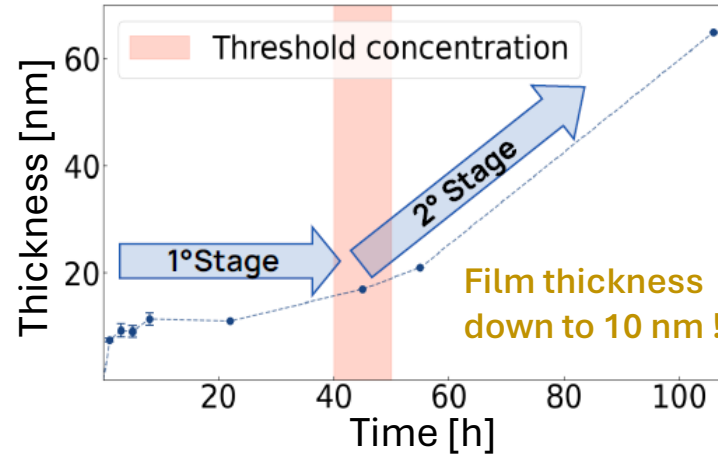
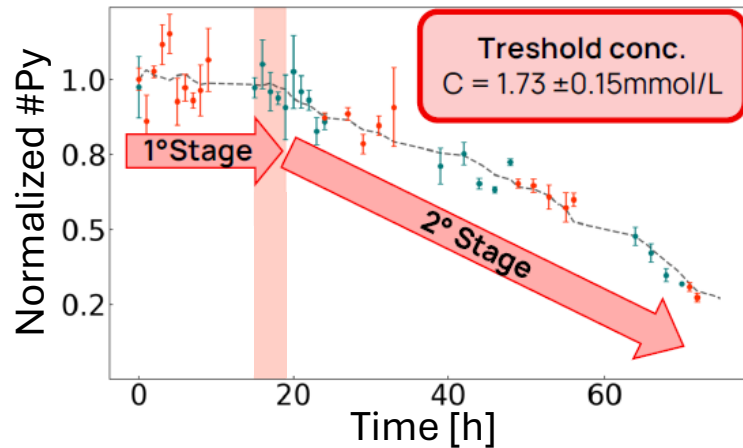


- Membrane collected at selected evaporation times
- UV-vis concentration tracking

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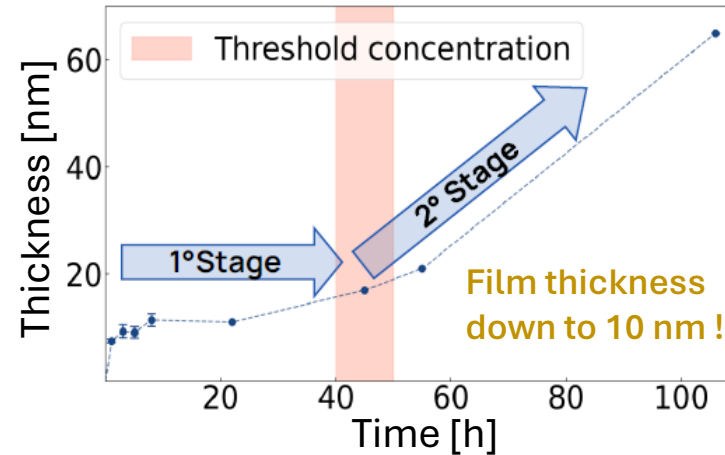
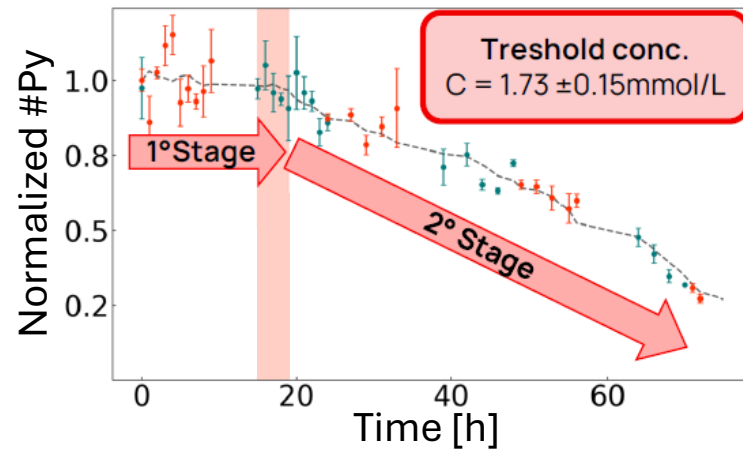
Two stage membrane formation

- Membrane collected at selected evaporation times
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Morphology & evaporation stages investigation

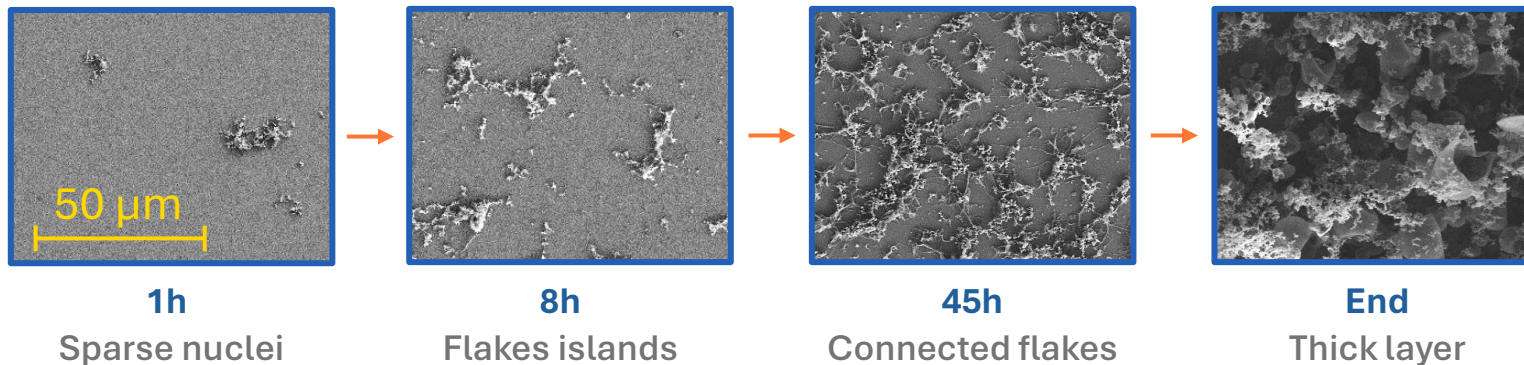
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- Time at the water interface



Two stage membrane formation

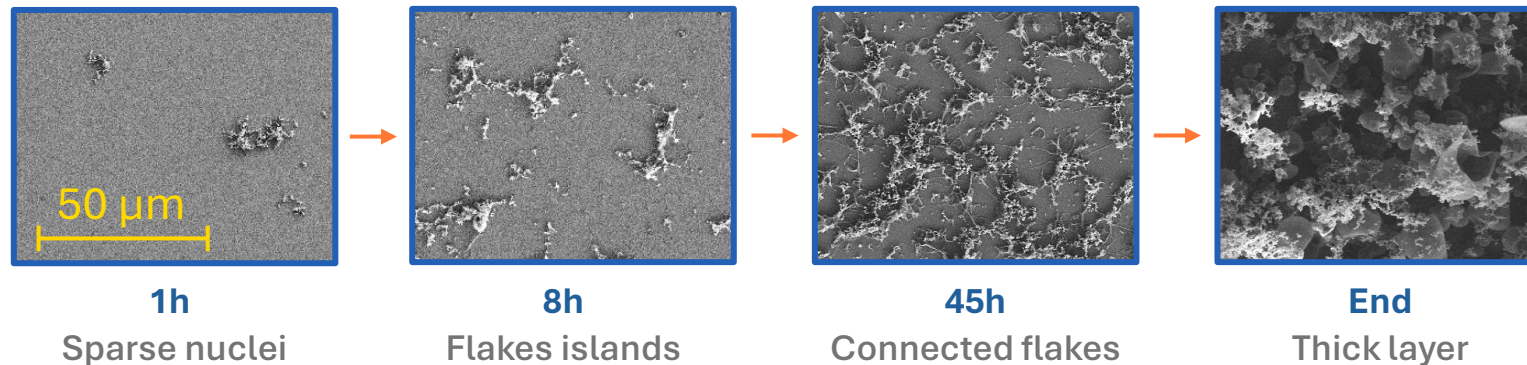
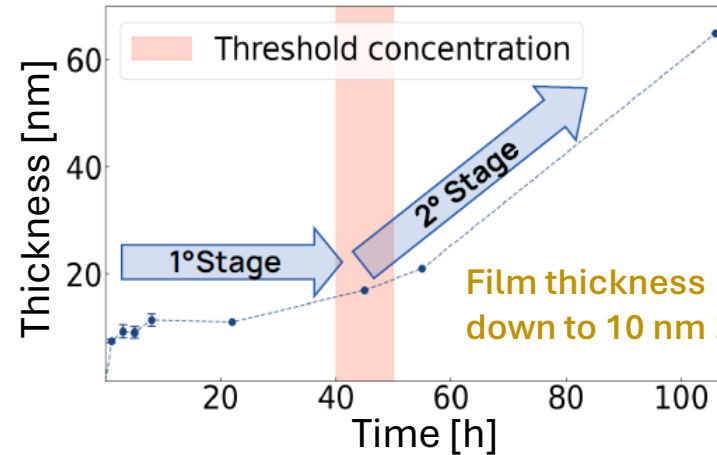
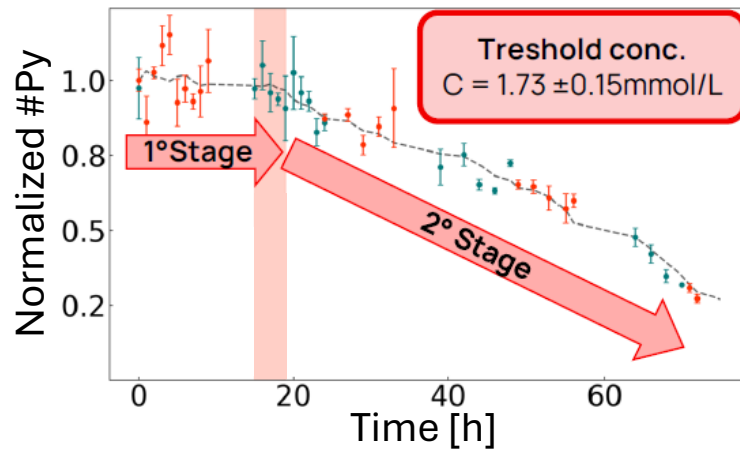
- Membrane collected at selected evaporation times
- UV-vis concentration tracking
- Early stage → **isolated flakes** and low precipitation
- Later stage → **thickness growth** and flake coalescence



Morphology & evaporation stages investigation

Production variables

- Polynes concentration (#Py)
- Time at the water interface

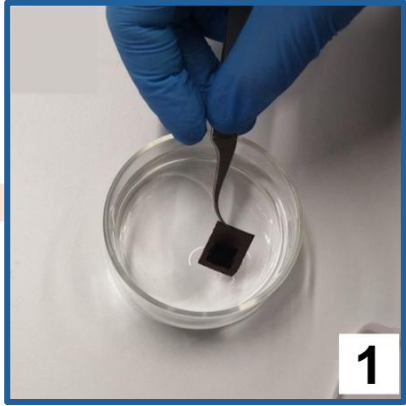


Two stage membrane formation

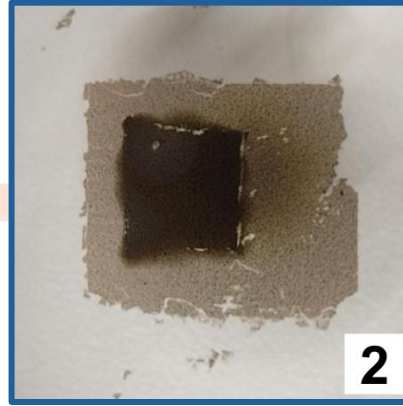
- Membrane collected at selected evaporation times
- UV-vis concentration tracking
- Early stage → **isolated flakes** and low precipitation
- Later stage → **thickness growth** and flake coalescence

Evaporation duration enables morphology tuning: **from clean ultrathin films to flake-covered DLT-like structures**

Target holder fishing for free standing configuration



Membrane transfer
on clean water



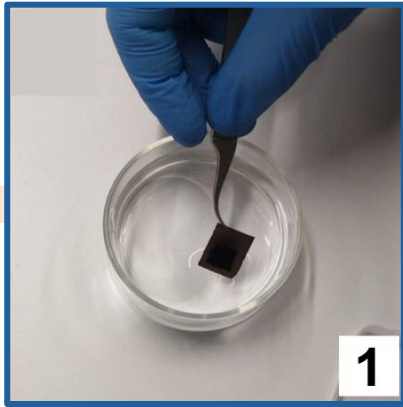
Membrane
floating



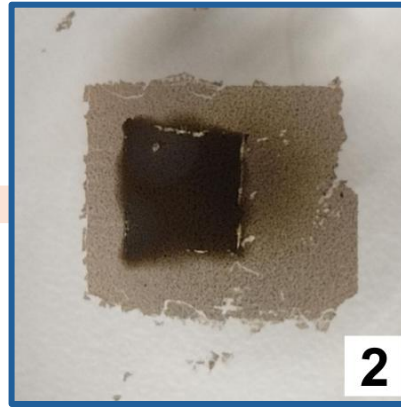
Membrane fishing
with target holder

- Membrane **directly fished from water** interface onto target holder

Target holder fishing for free standing configuration



Membrane transfer
on clean water

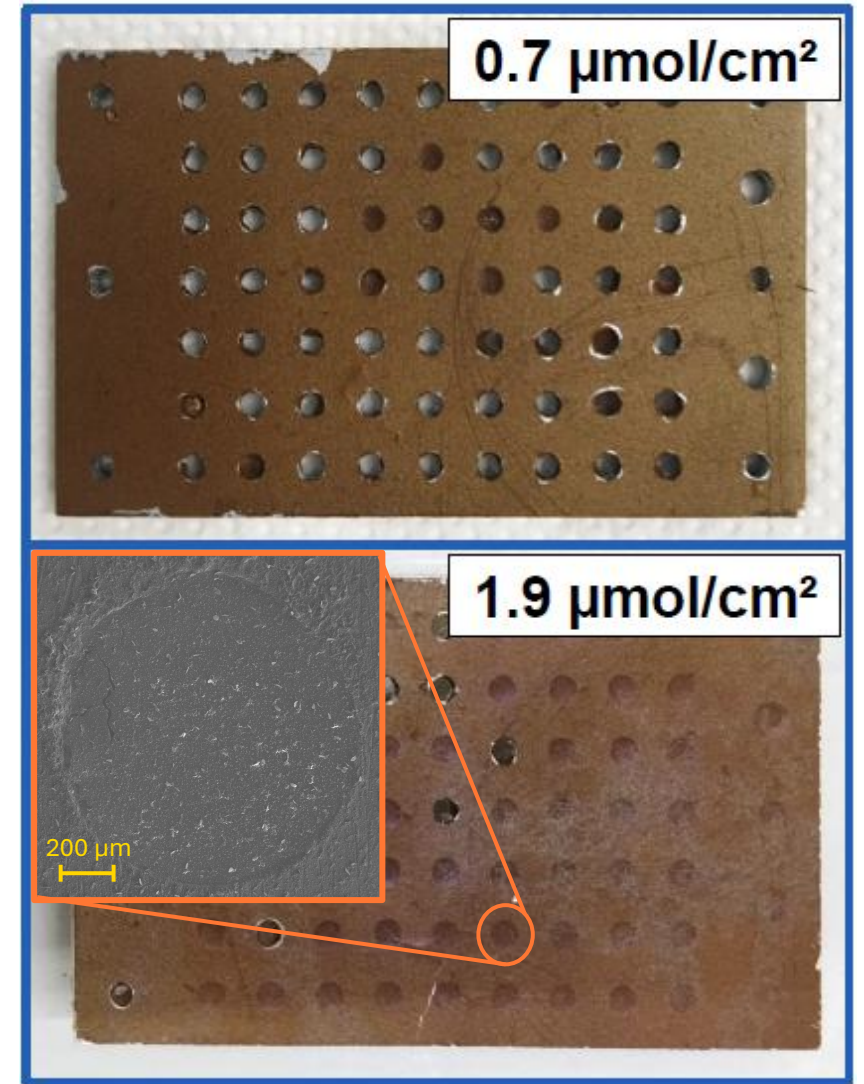


Membrane
floating

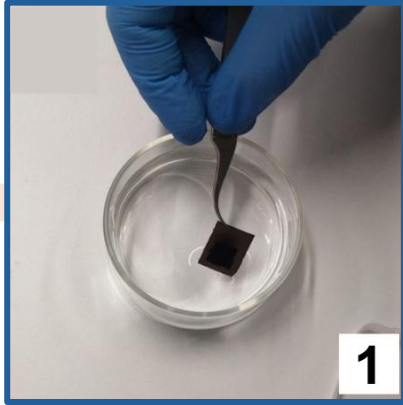


Membrane fishing
with target holder

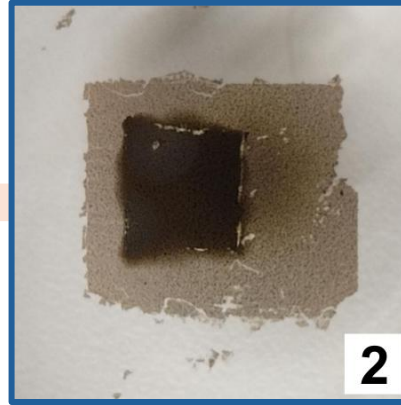
- Membrane **directly fished from water** interface onto target holder
- Method tested on holder with 1 and 3 mm diameter holes
- An **higher #Py/A improves the mechanical robustness** of the free standing configuration



Target holder fishing for free standing configuration



Membrane transfer
on clean water



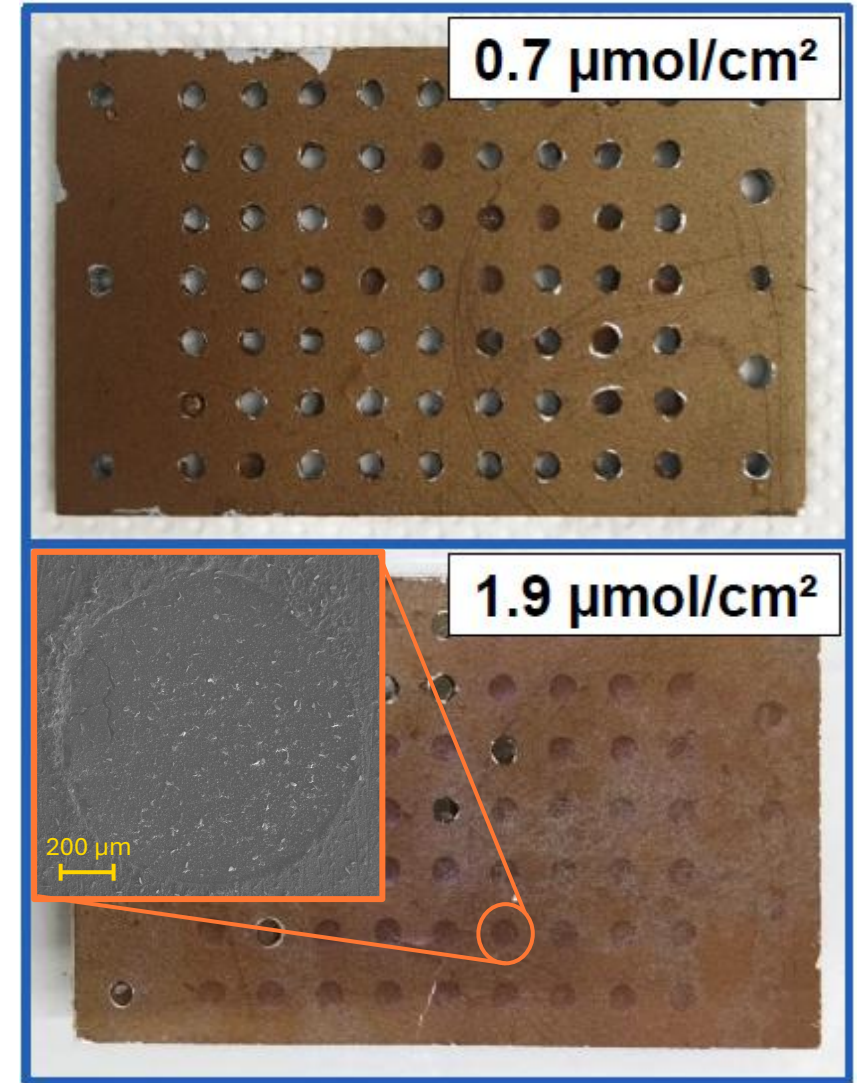
Membrane
floating



Membrane fishing
with target holder

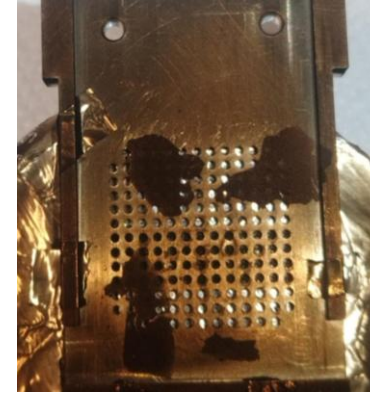
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Mountable, mm-scale, free standing
targets for laser experiments



Nanofoam deposition for DLT configuration

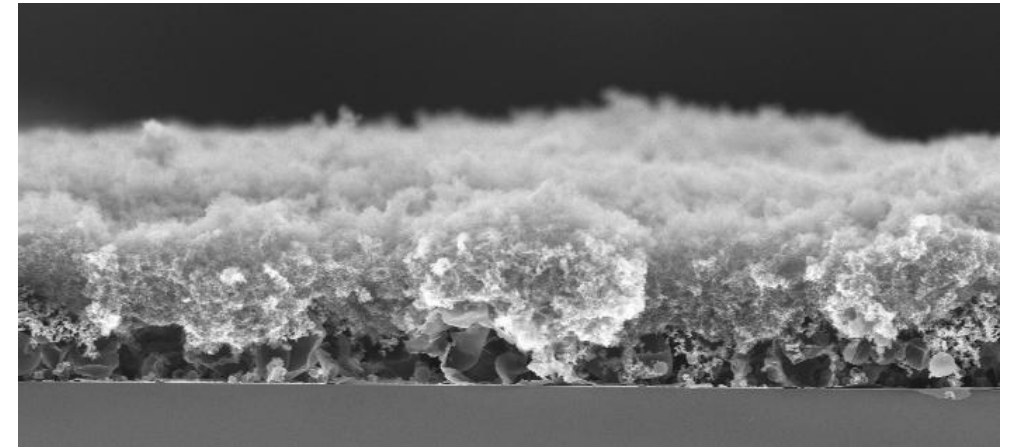
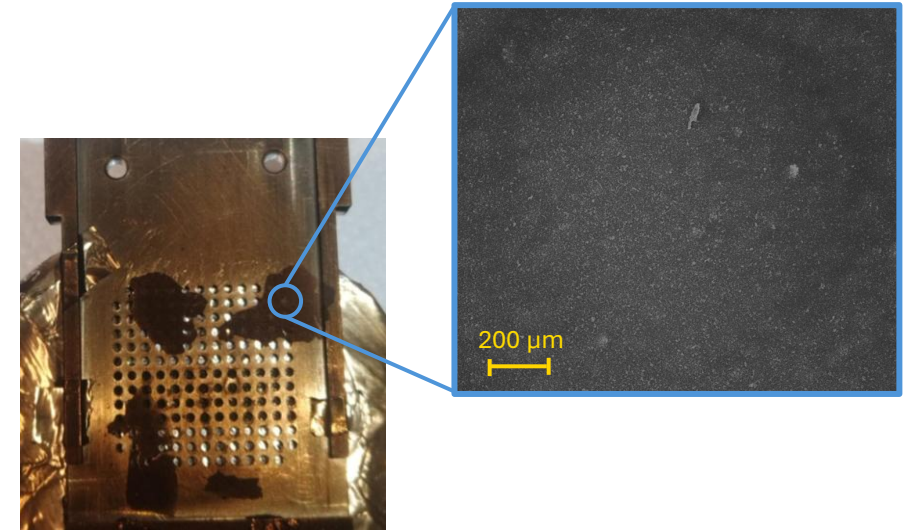
- Foam deposited directly on the free standing target



W. J. Ma et al., Physical Review Letters 122, 014803 (2019)

Nanofoam deposition for DLT configuration

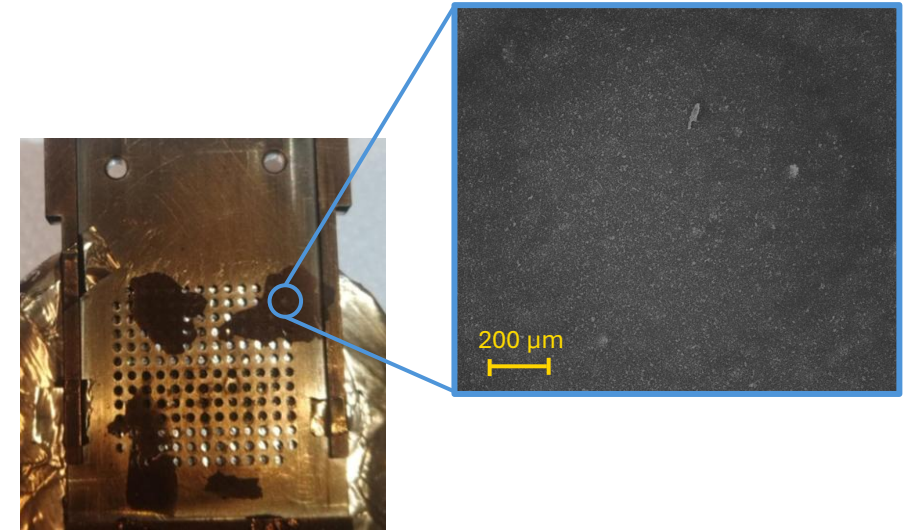
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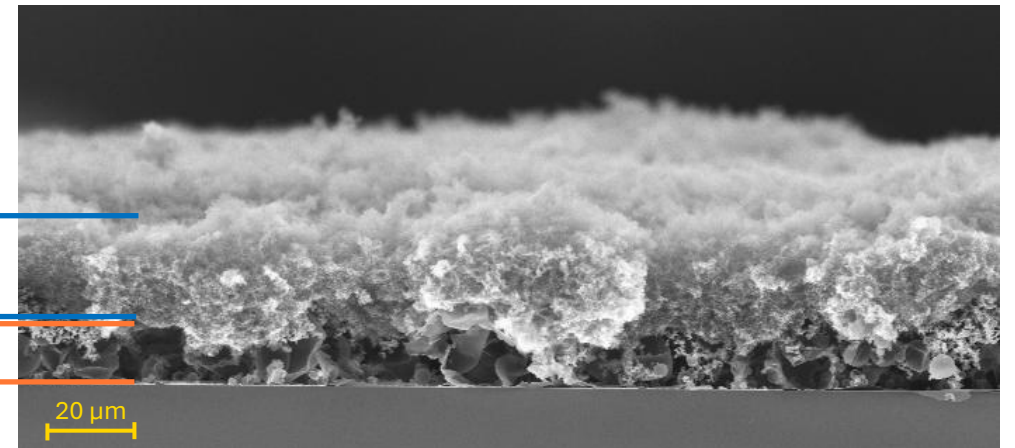
Nanofoam deposition for DLT configuration

- Foam deposited directly on the free standing target



Low-density Carbon nanofoam

Sp-rich Carbon Membrane

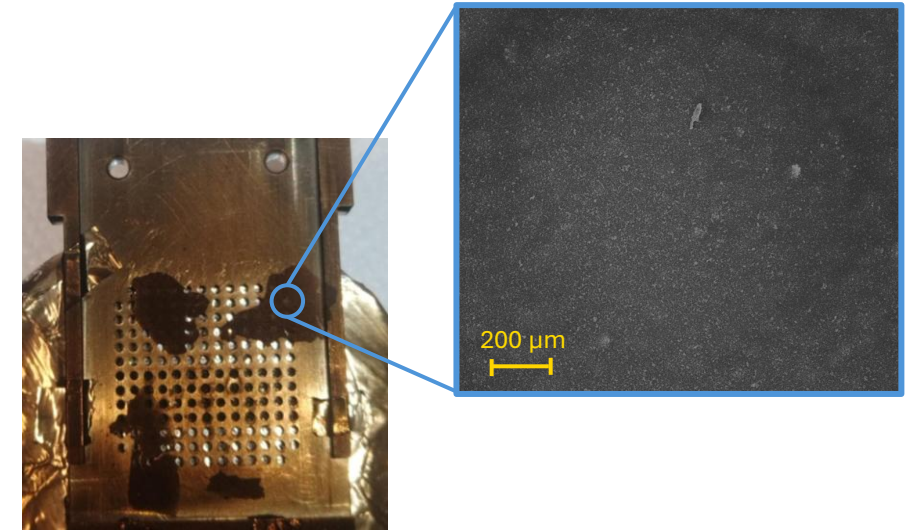


Chemical membrane + PLD nanofoam → Ultralight all-carbon DLT

W. J. Ma et al., Physical Review Letters 122, 014803 (2019)

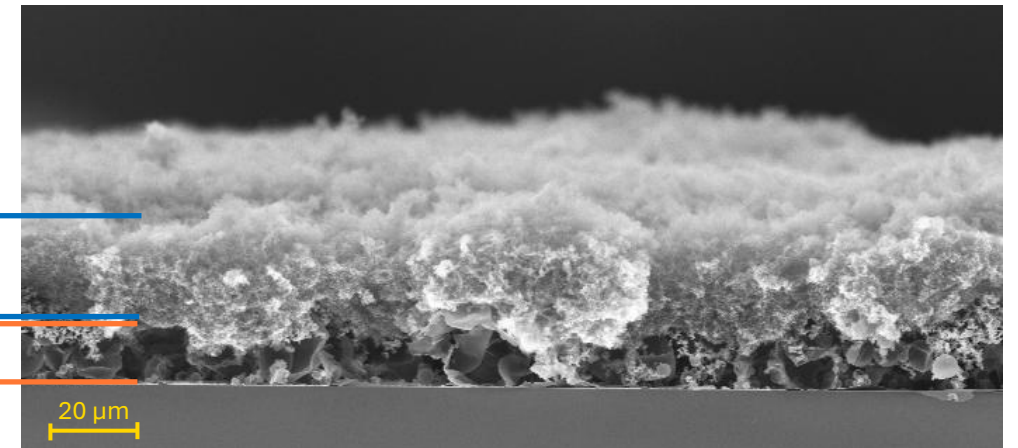
Nanofoam deposition for DLT configuration

- Foam deposited directly on the free standing target
- PLD carbon **nanofoam** offer **tunable density and morphology** to the extra layer
- Foam act as **low-density layer** that modifies laser propagation and enhances laser absorption



Low-density Carbon nanofoam

Sp-rich Carbon Membrane

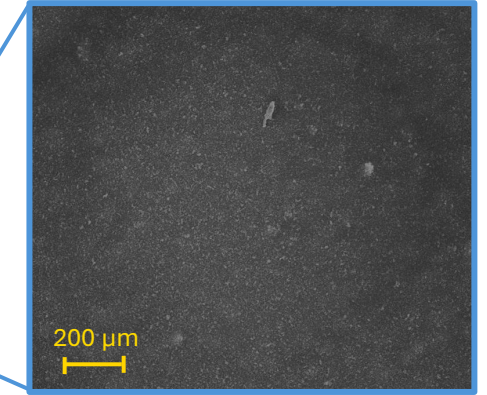
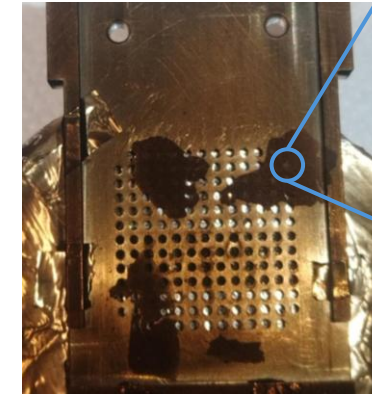


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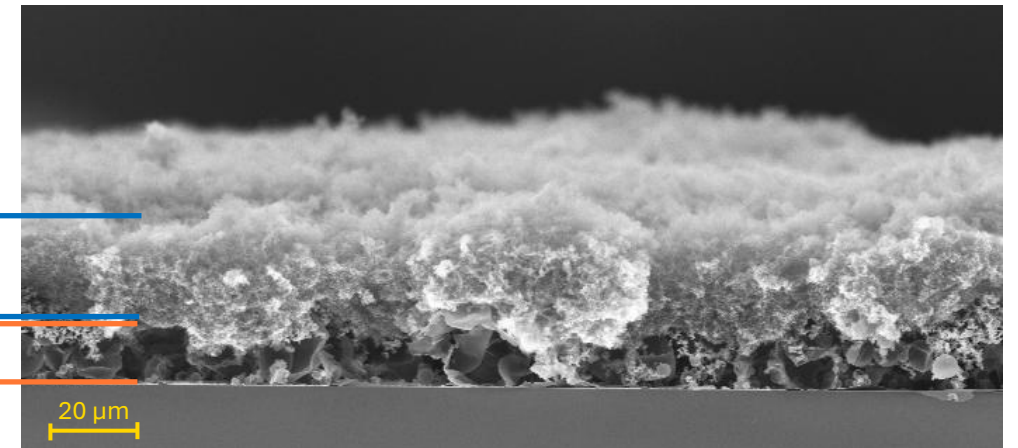
Nanofoam deposition for DLT configuration

- Foam deposited directly on the free standing target
- PLD carbon **nanofoam** offer **tunable density and morphology** to the extra layer
- Foam act as **low-density layer** that modifies laser propagation and enhances laser absorption
- Near critical foam front layer may promote **laser self-focusing** and **increase the effective radiation-pressure coupling** with the ultrathin film



Low-density Carbon nanofoam

Sp-rich Carbon Membrane



Chemical membrane + PLD nanofoam → Ultralight all-carbon DLT

W. J. Ma et al., Physical Review Letters 122, 014803 (2019)

Conclusion

- ✓ **Novel sp-rich, ultrathin carbon membranes** **successfully chemically produced** starting from cyclohexane-polyynes solution
- ✓ **Intrinsic double-layer architecture** composed by a dense ($\rho \sim 1.19 \text{ g/cm}^3$), **nanometric film** + ultralow-density ($\rho \sim 24 \text{ mg/cm}^3$) **micrometric flakes**
- ✓ **Polyynes areal density and evaporation stage** permits **tunable target properties** and morphology
- ✓ **Free-standing, mm-scale configuration** successfully obtained for laser-matter experiments

This work has been presented in the framework of the COST Action CA21128-PROBONO “PROton BORon Nuclear fusion: from energy production to medical applications”, supported by COST (European Cooperation in Science and Technology - www.cost.eu)

Conclusion

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What's next?

- **Optimization of the synthesis method** to obtain more reproducible targets
- Particle In Cell **simulation of laser-target interaction**
- **Target testing** under high-intensity laser irradiation

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Thank you for the attention

M. Passoni, et al. Plasma Physics and Controlled Fusion 61.1 (2019)

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

D. Orecchia et al., Small Structures, 5, 2300560 (2024)

A. Maffini, et al. Plasma Physics and Controlled Fusion 68 (2026)

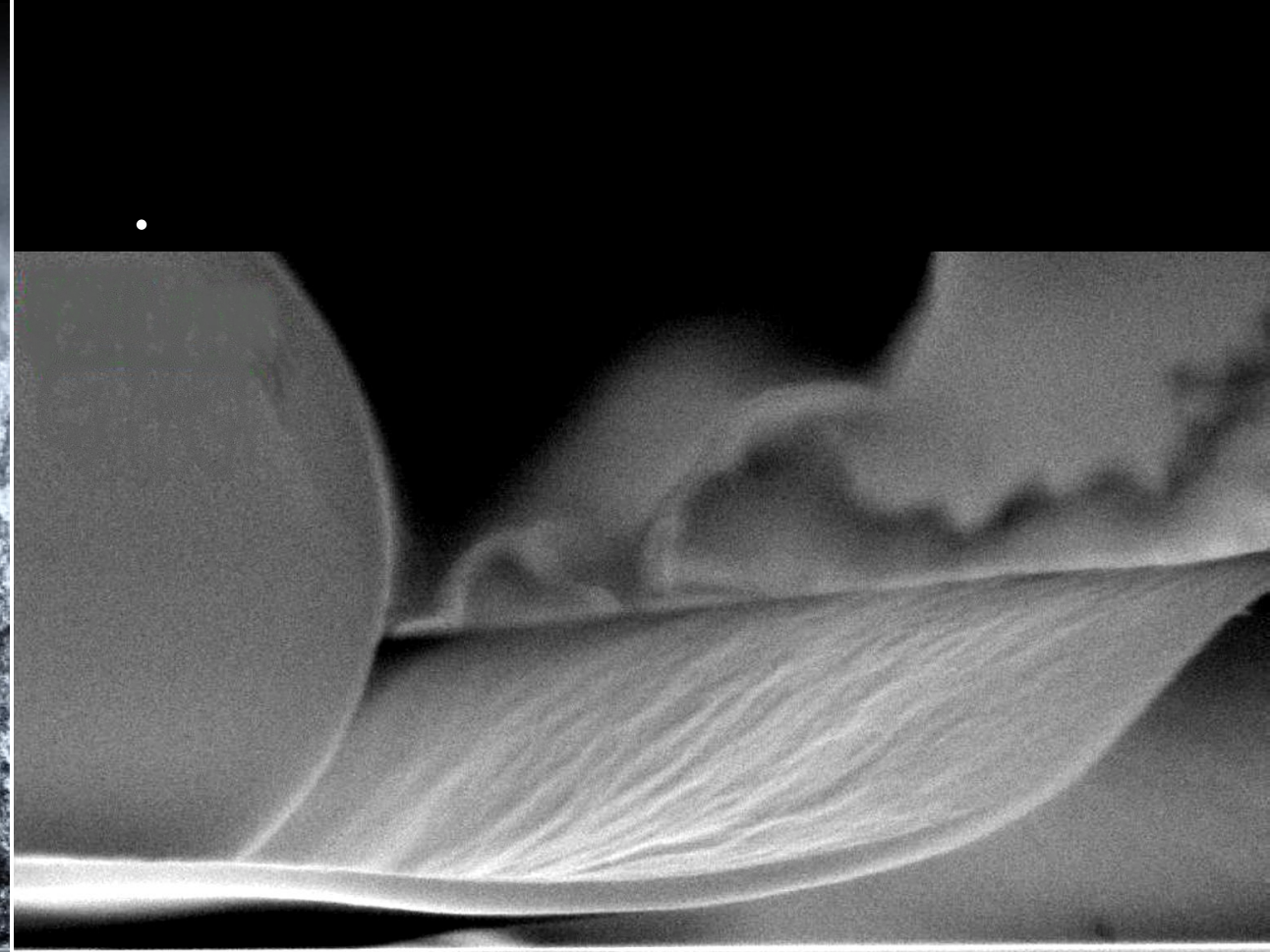
F. Cataldo, Carbon 43.13, 2792 (2005).

M. Agozzino et al., J. Phys. Chem. C, 2026.

W. J. Ma et al., Physical Review Letters 122, 014803 (2019)

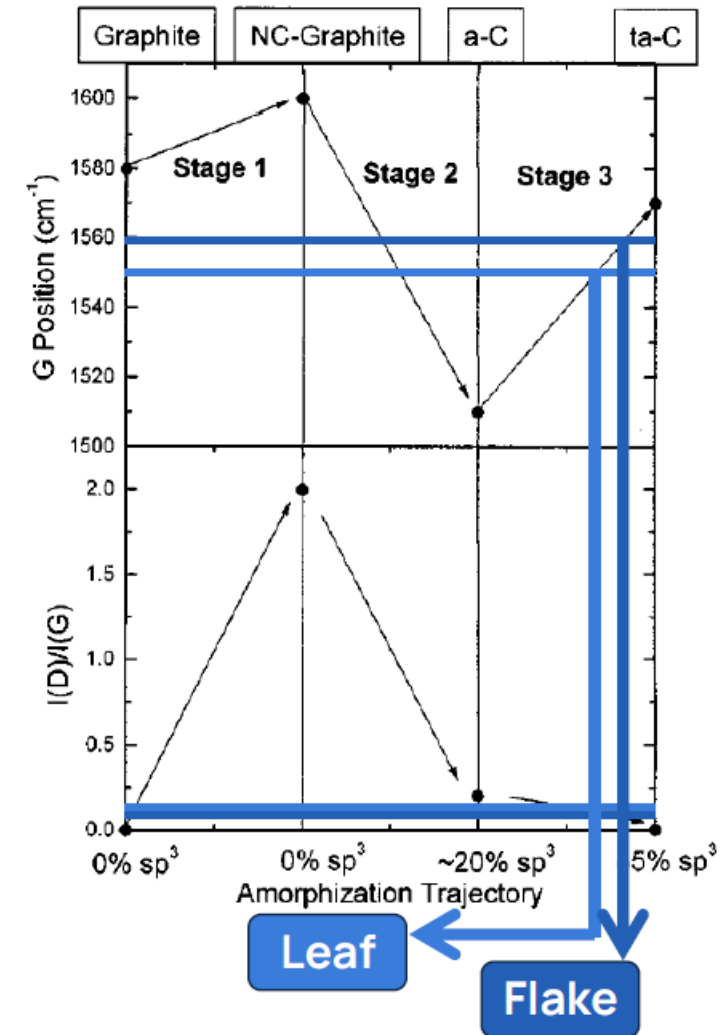


Back-up slides



Raman Spectroscopy

		G pos	D/G	sp long	sp short	sp/sp2
0.87 $\mu\text{mol}/\text{cm}^2$	Film	1560.95	0.108	2020.4	2160.3	0.107
	Flake	1561.41	0.104	2054.2	2161.2	0.268
	Leaf	1550.71	0.124	2066.9	2154.4	0.161
2.89 $\mu\text{mol}/\text{cm}^2$	Film	1559.9	0.105	2042.5	2157.8	0.207
	Flake	1559.7	0.101	2054.2	2158.2	0.268
	Leaf	1548.46	0.106	2069.9	2154.5	0.18



Raman Spectroscopy

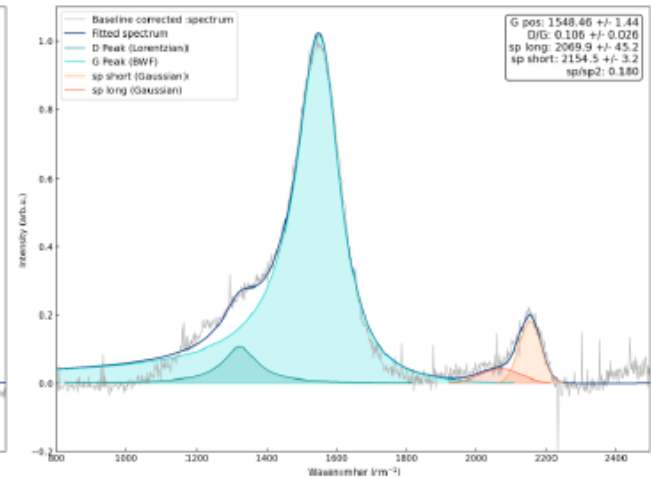
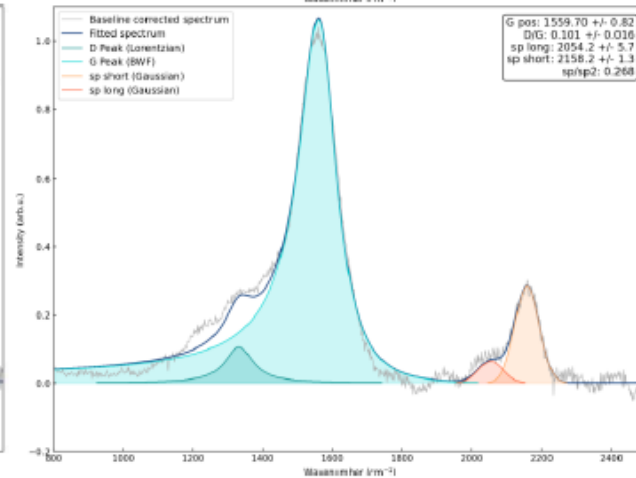
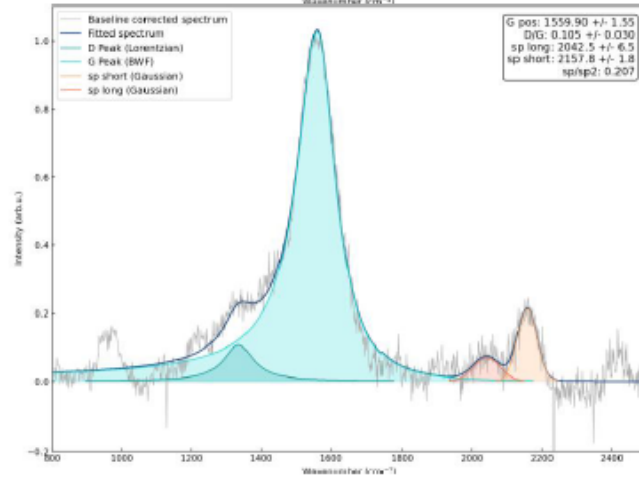
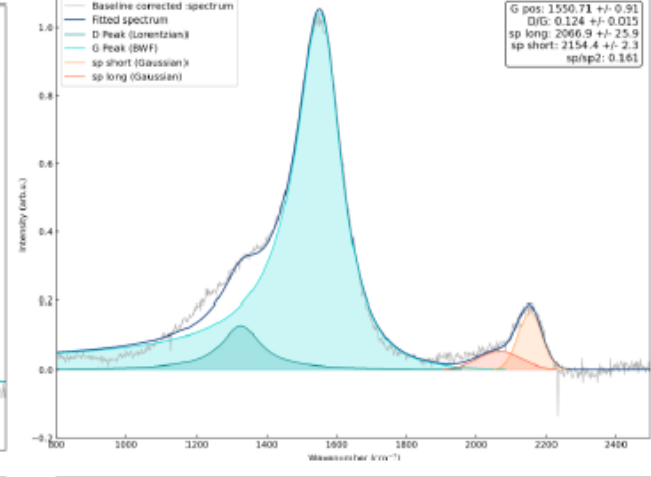
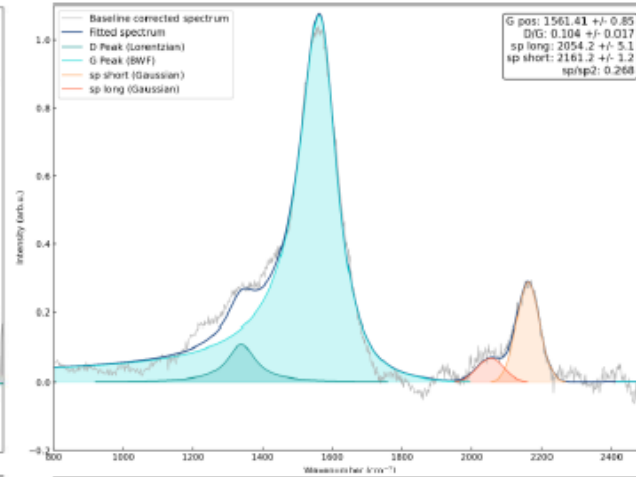
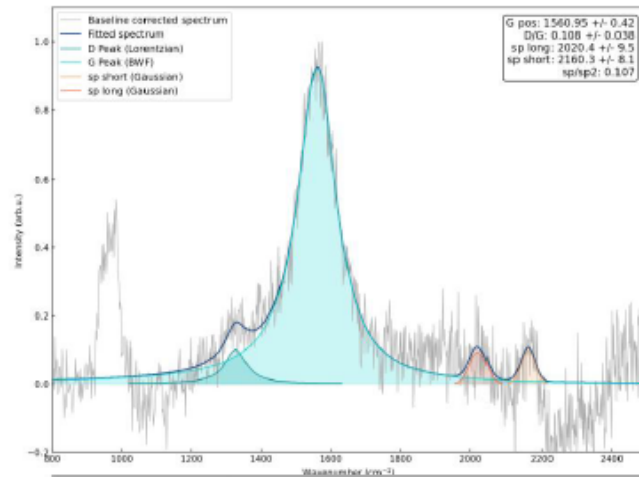
Film (5x400)

Flake (5x150)

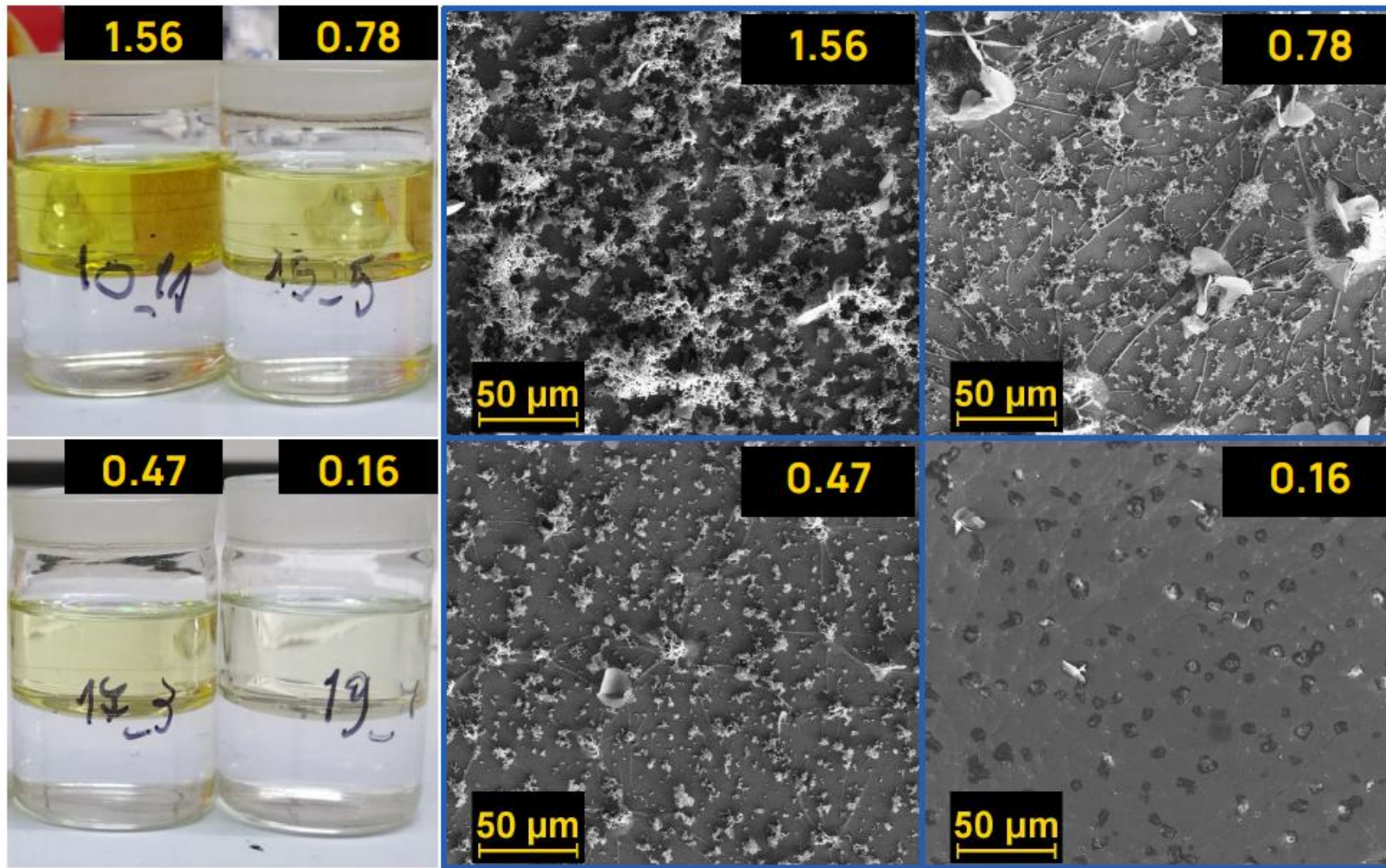
Leaf (5x300)

0.87
 $\mu\text{mol}/\text{cm}^2$

2.89
 $\mu\text{mol}/\text{cm}^2$



Different #Py/A



Different fishing times

