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MILANO 1863

Nanosecond Pulsed Laser Deposition of ultra-low density carbon foams for laser-driven ion acceleration

ERC-2014-CoG No.647554
ENSURE

Alessandro Maffini
(Politecnico di Milano)
Marseille, 08/09/2017

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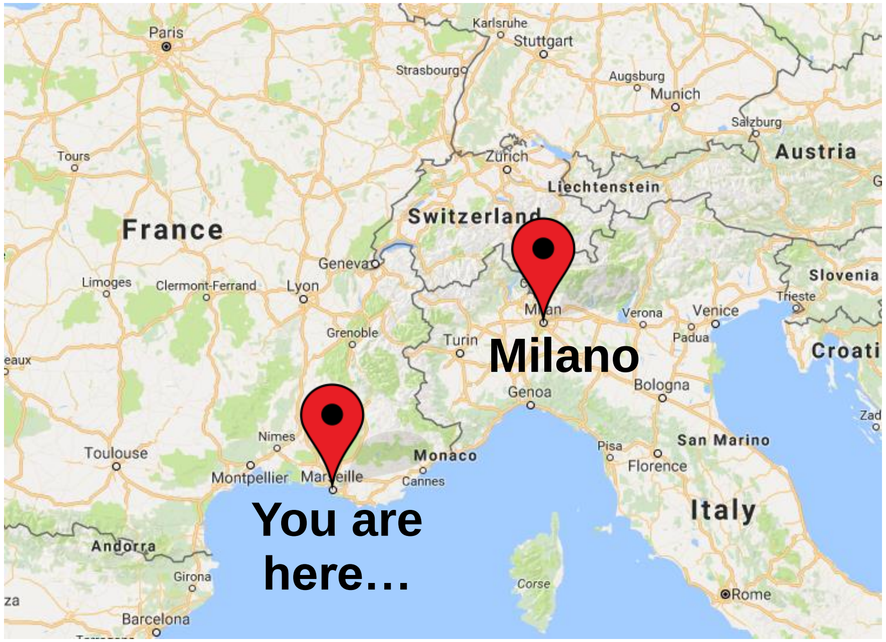

Politecnico di Milano (POLIMI) www.polimi.it

- Largest technical university in Italy, 6th top scoring in Europe
- More than 35’000 students, about 1400 faculty staff
- 32 BSc programmes, 34 MSc programmes, 18 PhD programmes
- 24 ERC projects hosted since 2008

ENSURE

Exploring the New Science and engineering unveiled by Ultraintense ultrashort Radiation interaction with mattEr

erc

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DIPARTIMENTO DI ENERGIA

ERC-2014-CoG No.647554

ERC consolidator grant: 5 year project, from September 2015 to September 2020

Goal: To **E**xplore the **N**ew **S**cience and engineering unveiled by **U**ltraintense, ultrashort **R**adiation interaction with matt**E**r

Hosted @ NanoLab, Energy department, Politecnico di Milano

Principal investigator:
Matteo Passoni, Associate professor

Team: 2 Associate Professor, 1 Assistant Professor, 4 Post-Docs, 3 PhDs + master students and support from NanoLab people

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ENSURE

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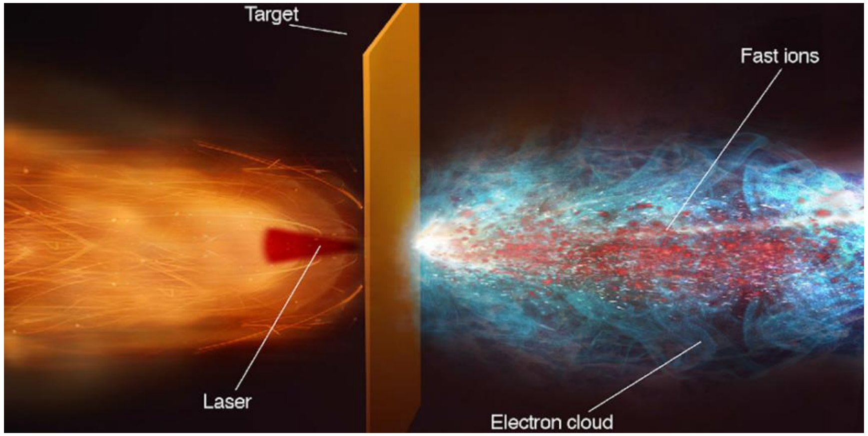
DIPARTIMENTO DI ENERGIA

Laser-matter interaction is a cornerstone of ENSURE

Laser-driven particle acceleration

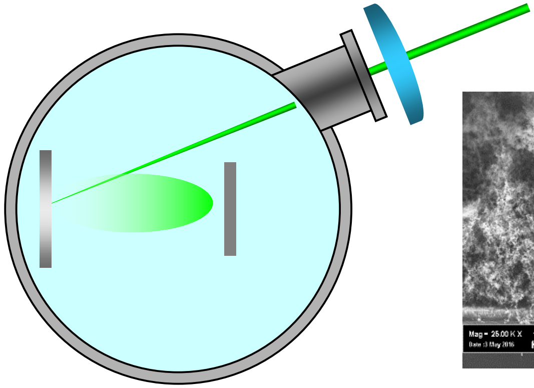
Ultraintense, ultrashort pulses on solid targets

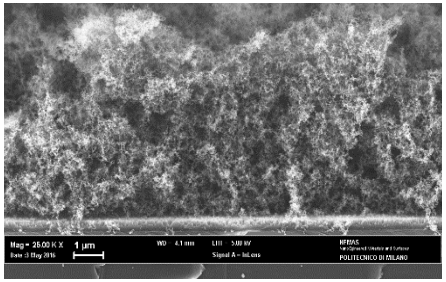


- Theoretical/Numerical investigation
- Experimental campaigns

Pulsed Laser Deposition

PLD of advanced nano-engineerd targets





- Mostly **<u>ns-PLD</u>** so far
- fs-PLD under development

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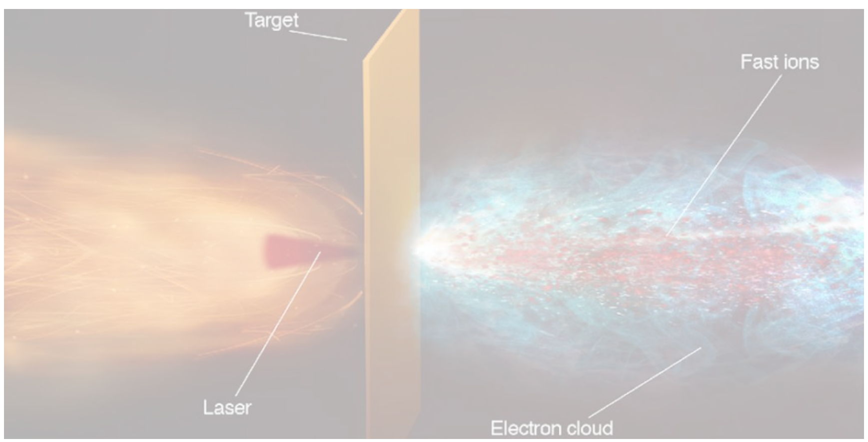

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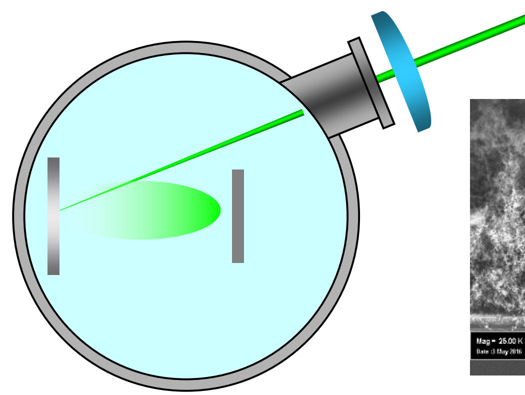

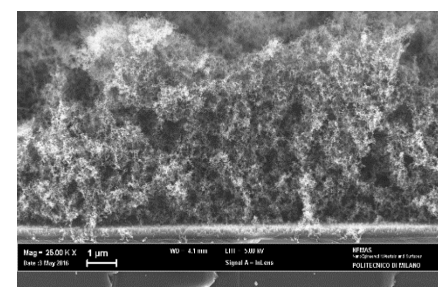

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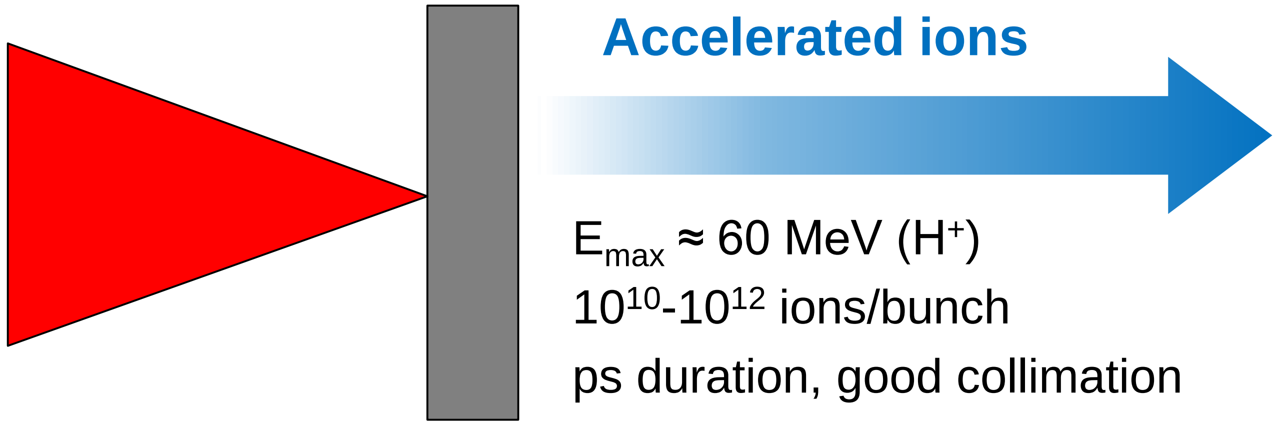
Laser-Driven ion acceleration

Laser parameters:

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



Accelerated ions

E_{max} ≈ 60 MeV (H^+)
10^{10}-10^{12} ions/bunch
ps duration, good collimation

A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Phys., 85 751 (2013)

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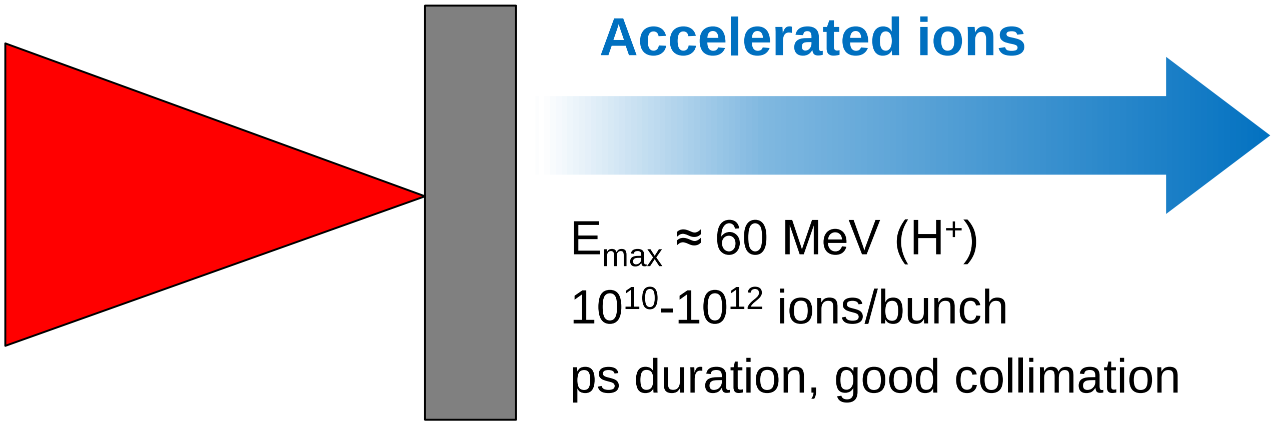

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We want Laser-driven ion **beams**…

- Cancer Hadrontherapy
- Material science
- Non-destructive diagnostics (e.g. PIXE)
- Laser-driven nuclear physics
- …And much more!

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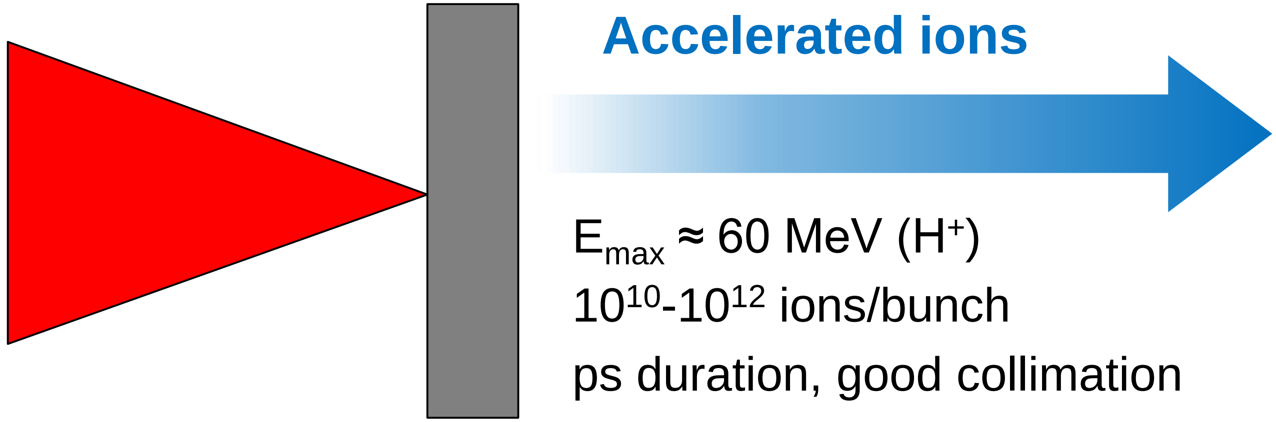

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….but there are **issues to be addressed**

- Better understanding
- Increase $\mathbf{E_{max}}$
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- Increase **rep. rate** (up to 10 Hz and more)

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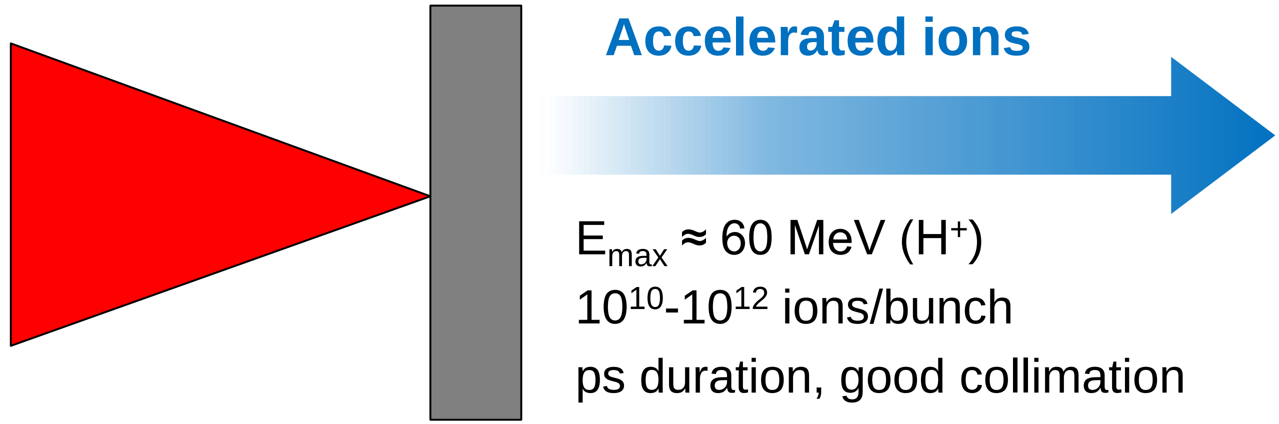

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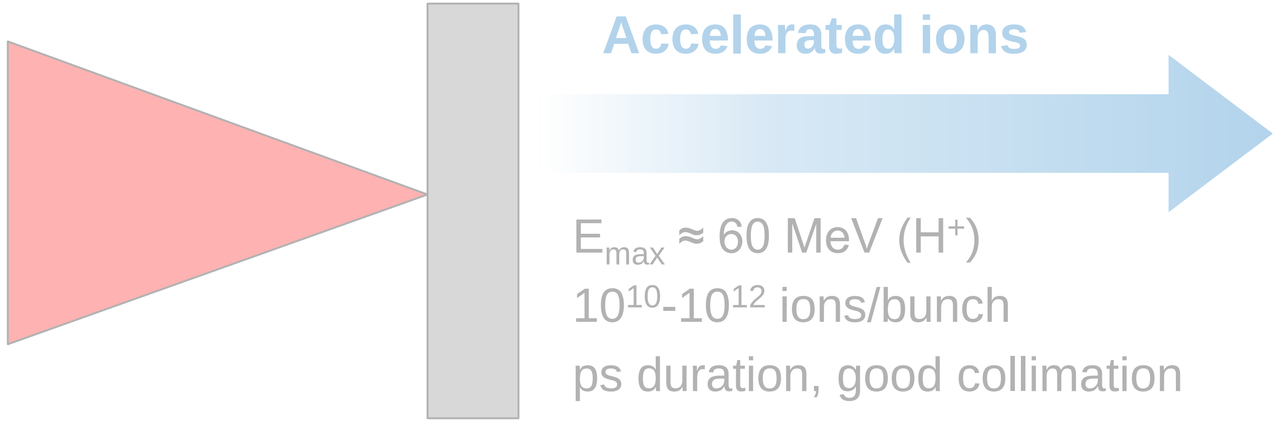

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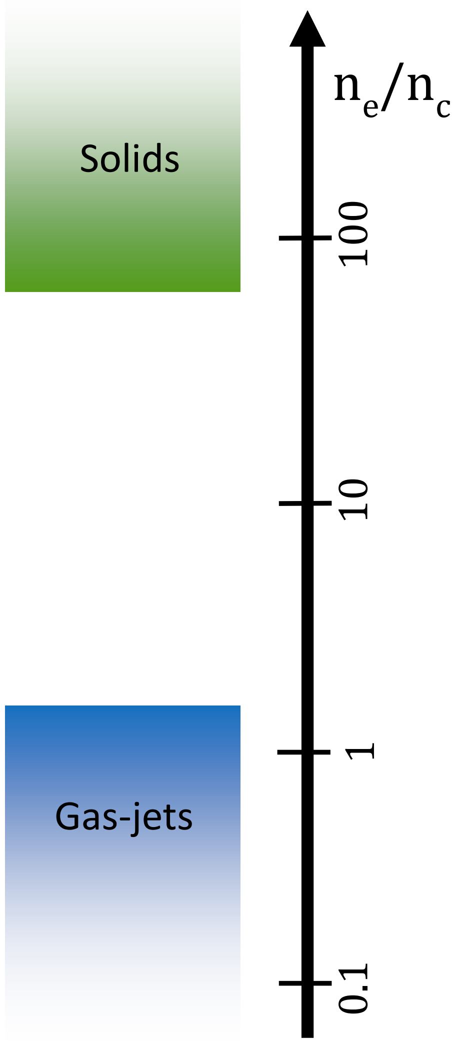
$$n_c \approx 6\ \mathrm{mg/cm^3}$$

(@ λ=800 nm, γ=1)



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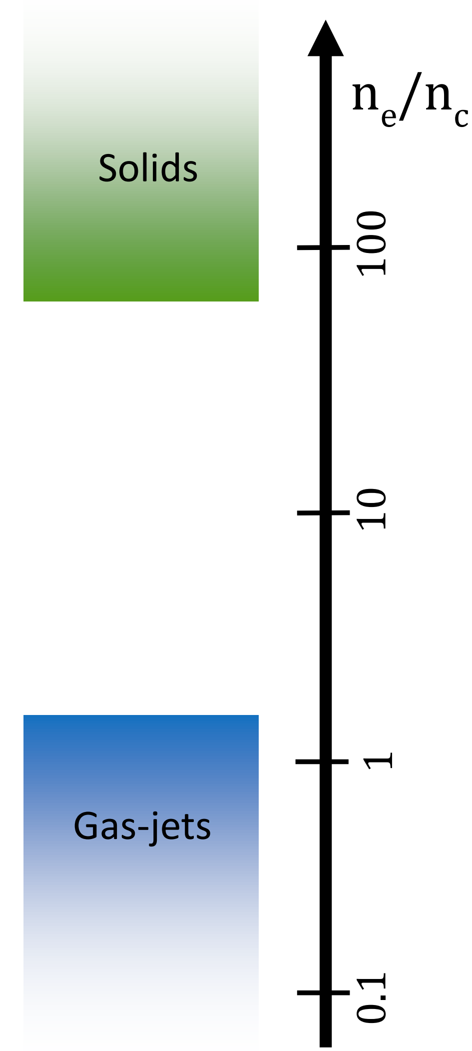

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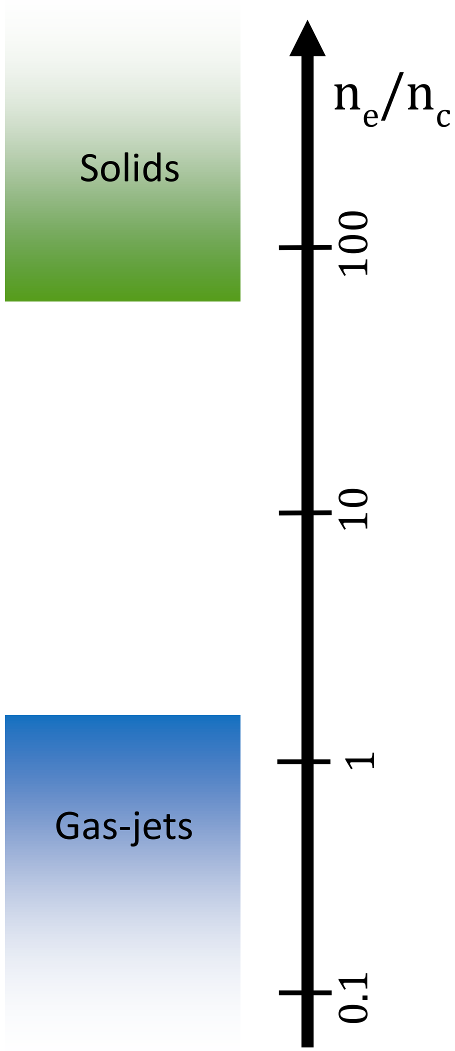

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strong laser-plasma coupling

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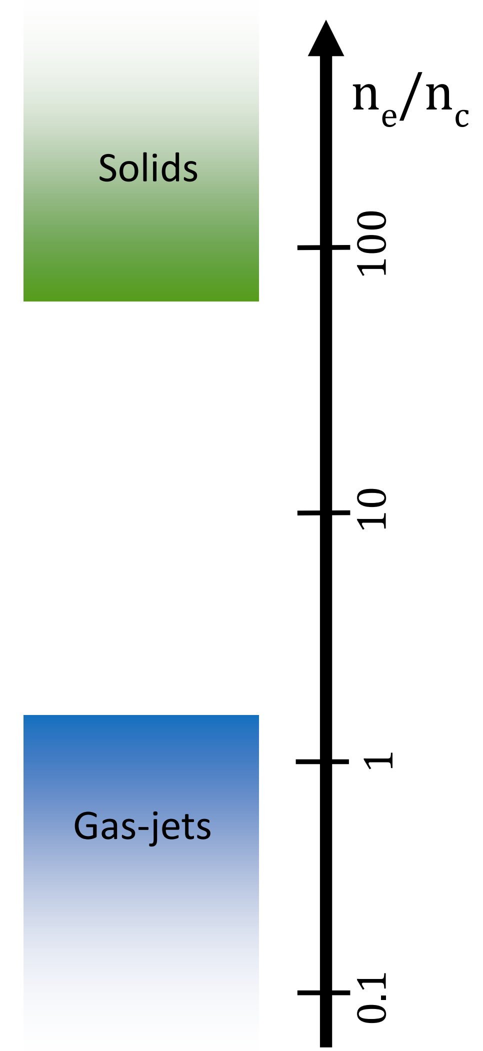

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Potential for **enhancing** laser-driven **acceleration**!

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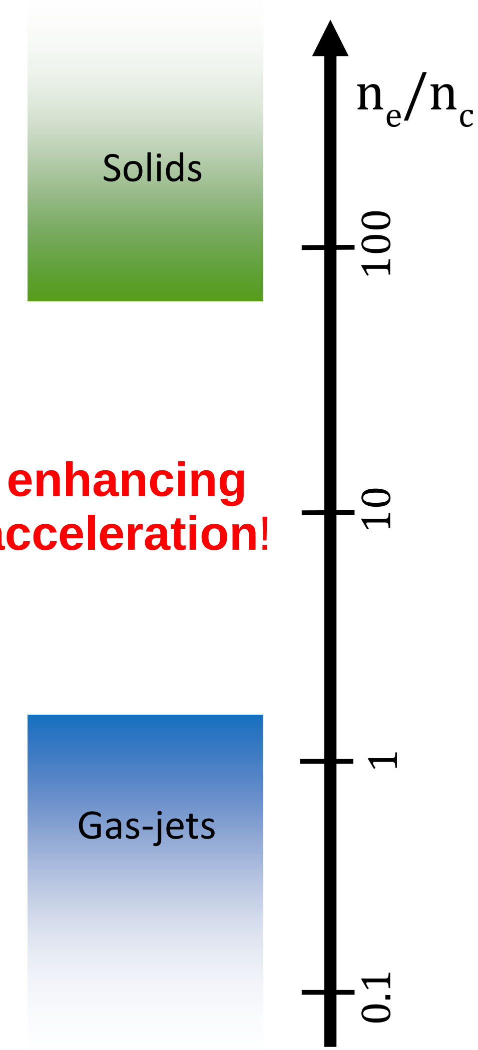
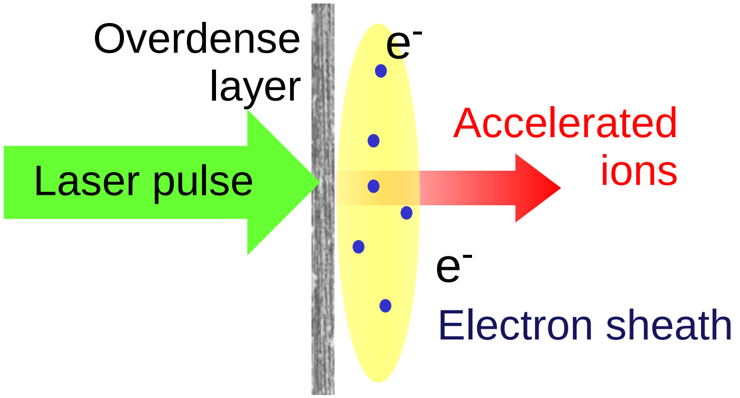


Foam-attached targets for Enhanced-TNSA

Conventional target

(Micrometric thick solid foil)



1) **<u>n >> nc: Surface interaction</u>**
2) Hot e^- population is excited
3) Electron sheath beneath the target
4) Quasi-static accelerating field arises
5) H^+ contaminants accelerated

Target Normal Sheath Acceleration (TNSA)

T. Nakamura *et al*., Phys. Plasmas, 17 113107 (2010)

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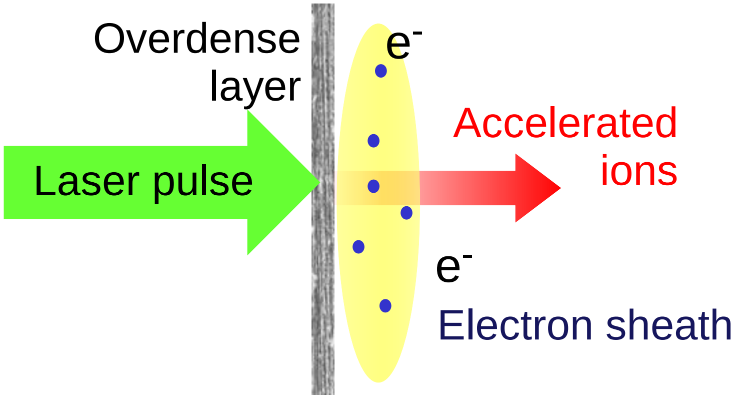

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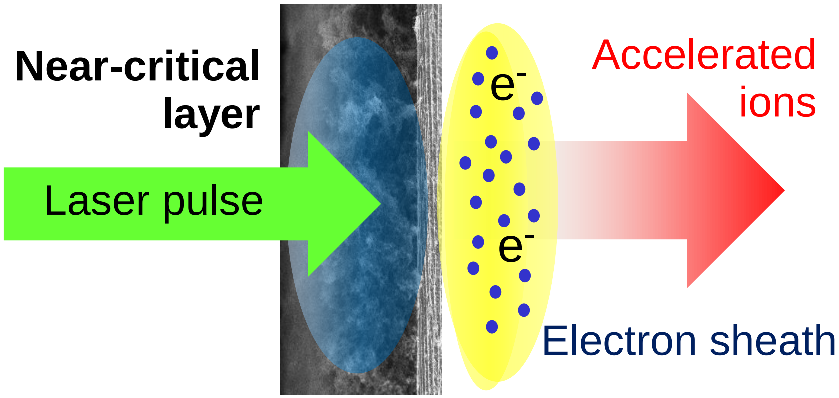
Advanced target

(Multi-layer, Foam-attached micrometric foil)



1) **n ≈ nc: Volume interaction**
2) ↑ Energy conversion, ↑ Hot e^- temperature
3) More e^- in the electron sheath
4) Stronger accelerating field
5) Accelerating process is enhanced

Enhanced TNSA

T. Nakamura *et al.*, Phys. Plasmas, 17 113107 (2010)

Near-critical layer requirements

1. Near-critical **<u>density</u>** (ρ **≈10 mg/cm^3**)
2. Micrometric **<u>thickness</u>** (few **μm** up to tens of **μm**)
3. **<u>Homogeneity</u>** on the laser spot size scale (**≈ 5 μm**)
4. **<u>Uniformity</u>** on the target size scale (**≈ 5 cm**)
5. Compatibility with **<u>fragile/thin substrates</u>** (**≈ 100 nm**)
6. Suitable for **<u>high rep. rate</u>** experiments (up to **kHz!**)

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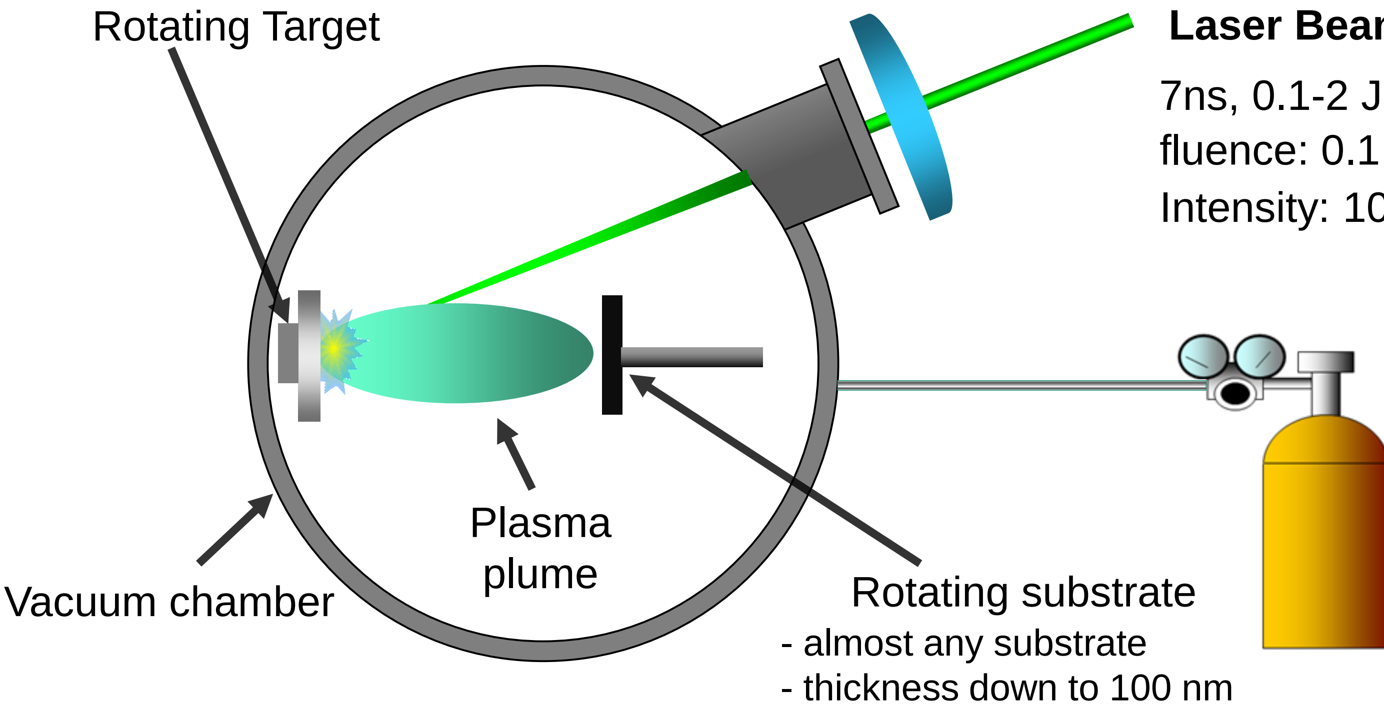
Pulsed Laser Deposition
of void-rich, **carbon foam**-like structures!

A.V. Rode, E.G. Gamaly and B. Luther-Davies, App. Phys. A **70** 135-144 (2000)

A. Zani et al., Carbon, **56** 358 (2013)
I. Prencipe et al., Plasma Phys. Control. Fusion **58** (2016) 034019

ns Pulsed Laser Deposition (PLD) in a background gas

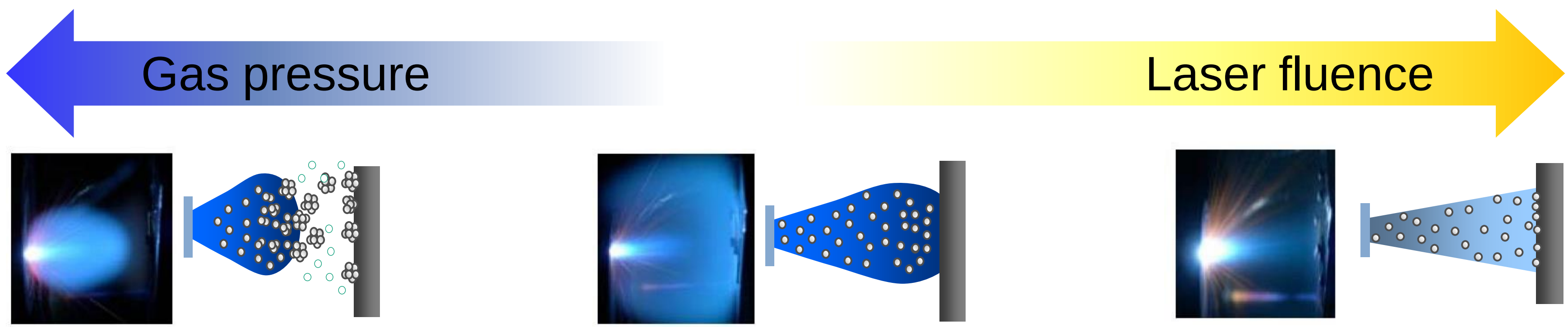


Laser Beam λ= 266, 532, 1064 nm

7ns, 0.1-2 J, 10 Hz
fluence: 0.1 - 20 J/cm^2
Intensity: 10^7 – 2×10^9 W/cm^2

Background Gas

- Inert (He, Ar..)
- Reactive (O_2)



Foam property control

Nano-scale

- Crystalline structure
- Composition

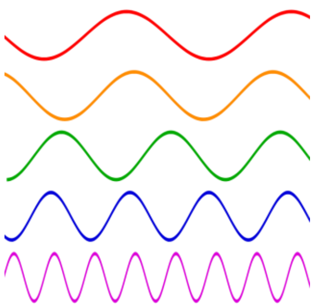
Micro-scale

- Average density
- Morphology
- ….

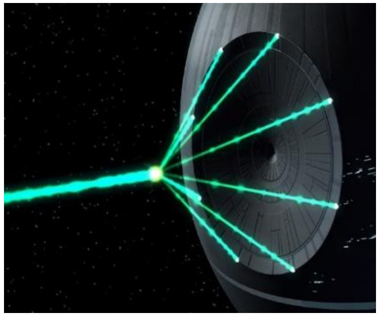
Macro-scale

- Uniformity
- Thickness profile

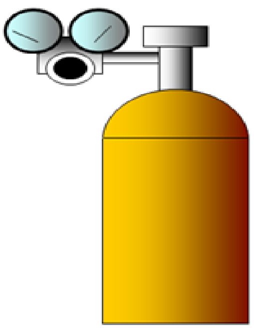
Laser Wavelength



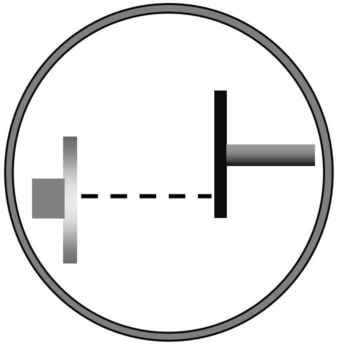
Laser Fluence



Gas pressure



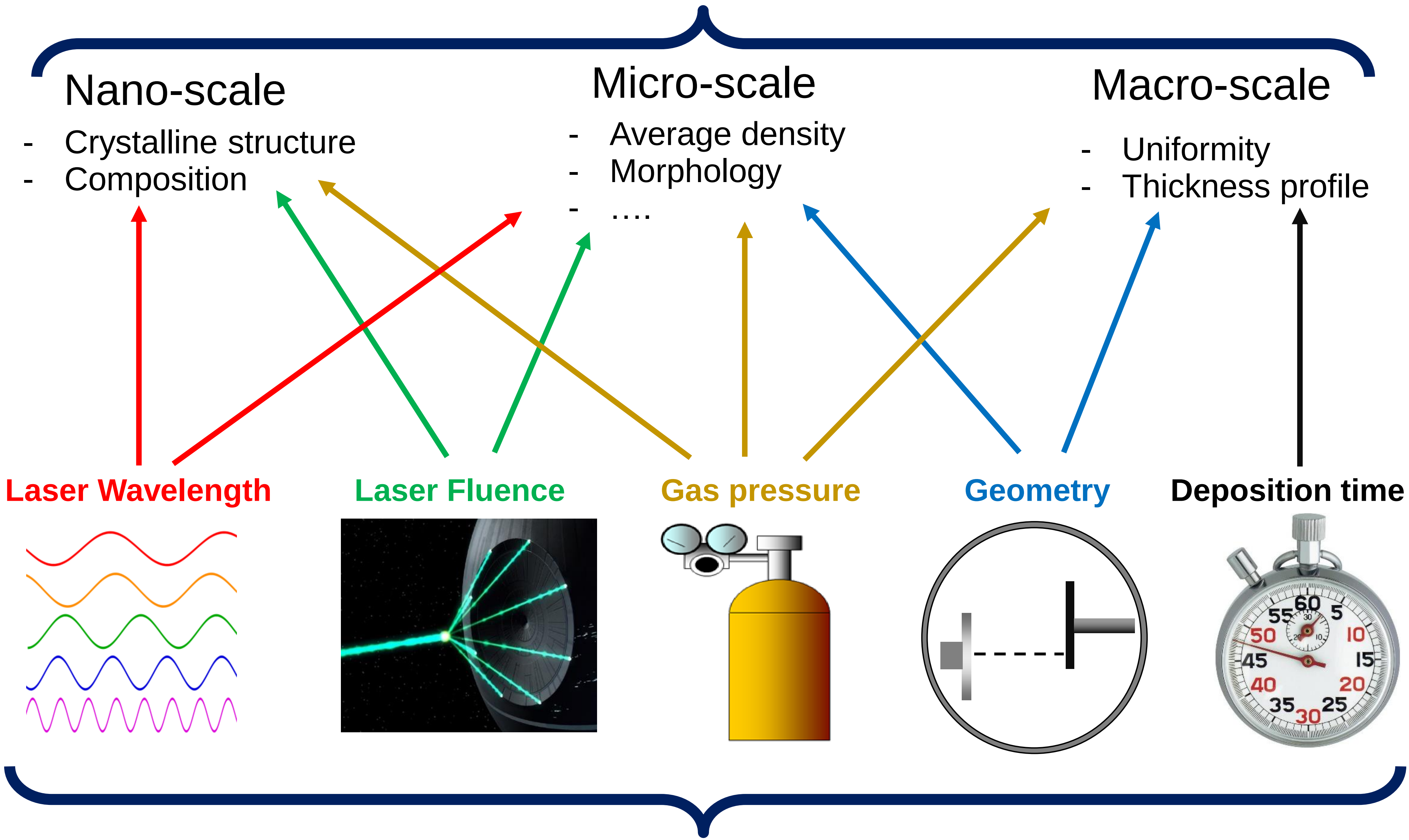
Geometry



Deposition time

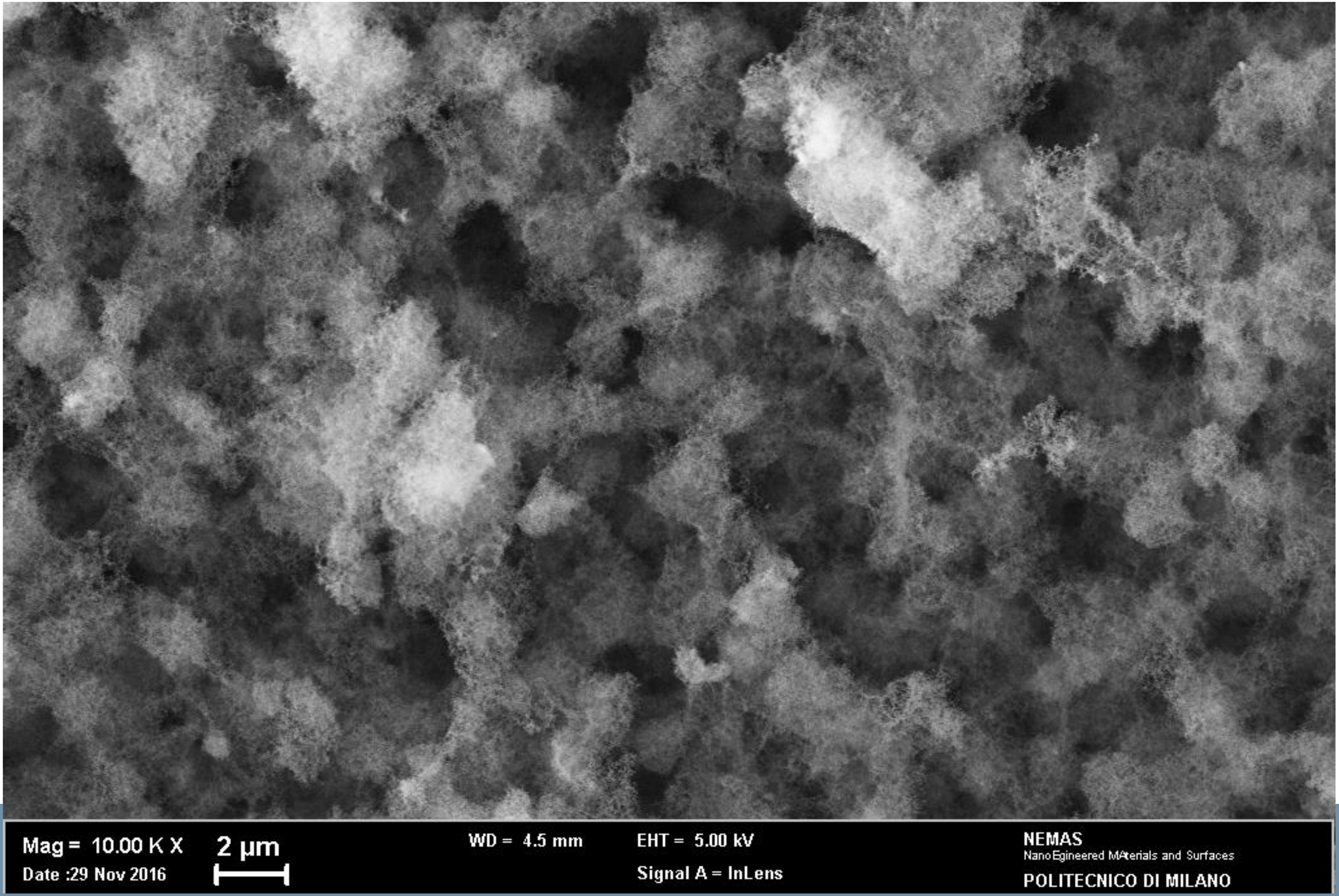
PLD process parameters

Foam property control

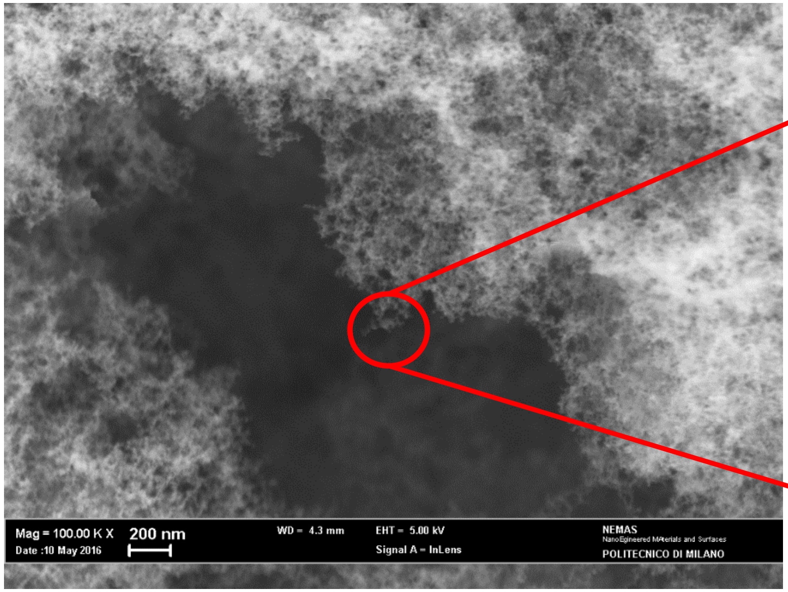


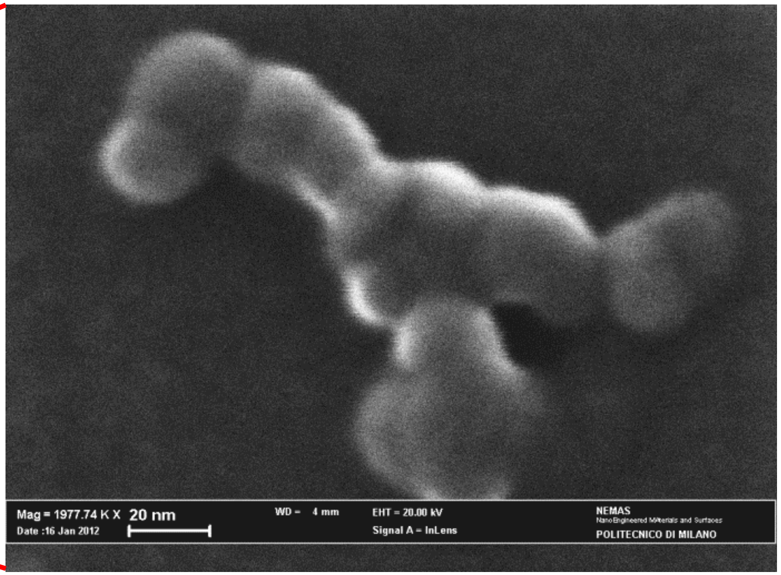
PLD process parameters

How the foam looks like…



Building blocks: carbon nanoparticle

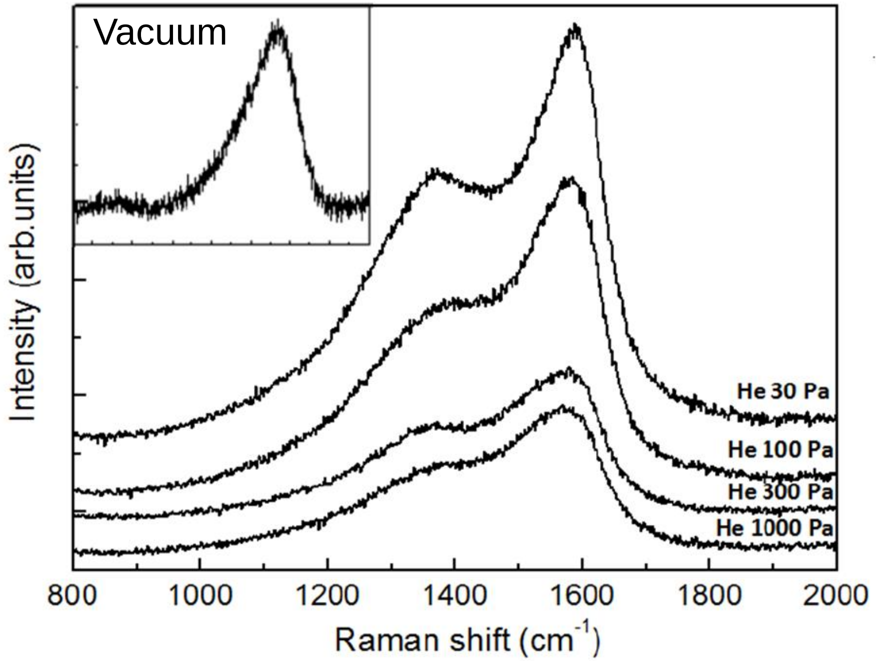




<u>Elementary constituents:</u>
10-20 nm nanoparticles

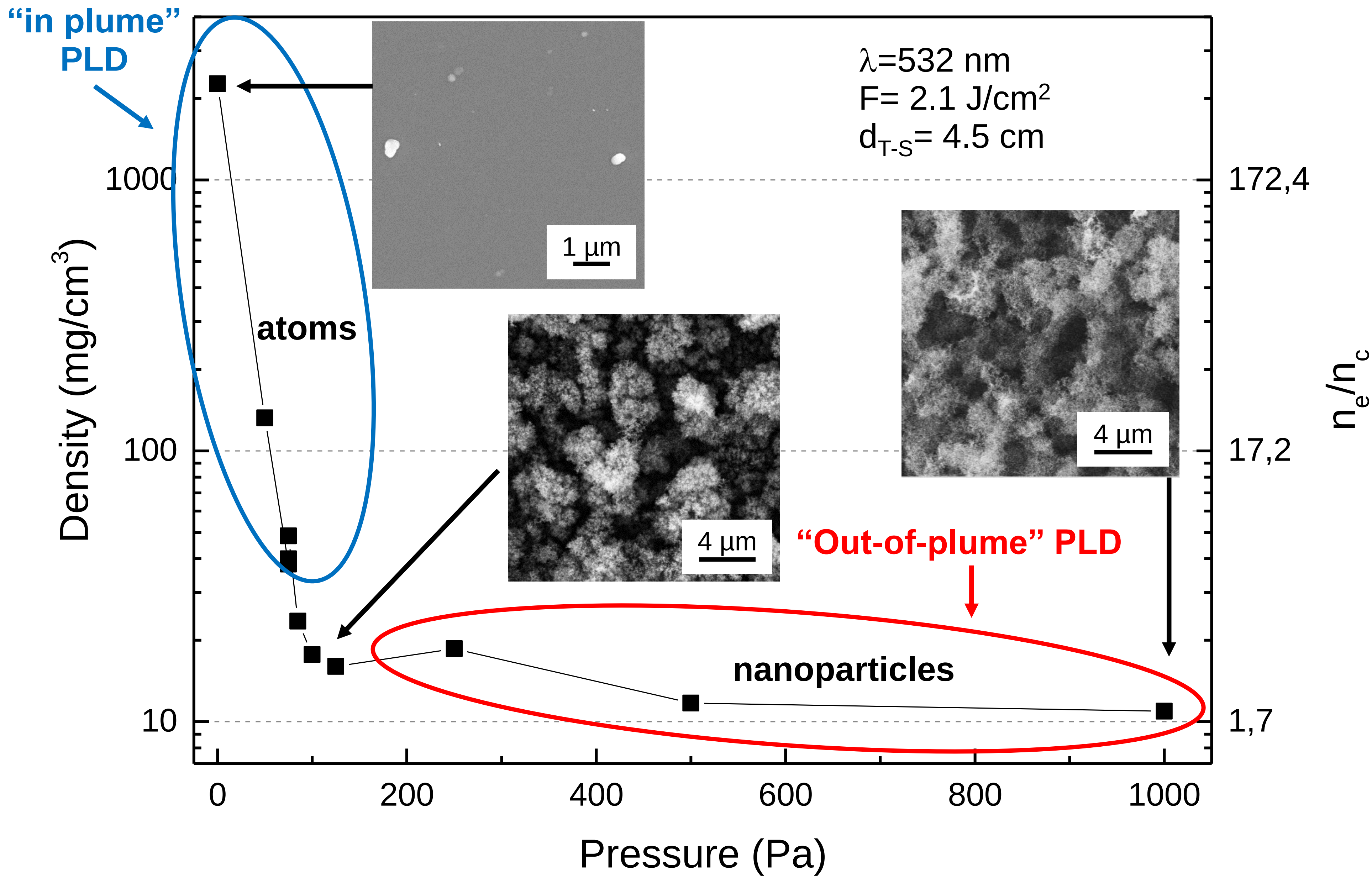
<u>C-C bonding:</u>
Nearly pure sp^2
odd-membered rings and
few chain-like structures

<u>Crystalline structure:</u>
Topologically disordered domains,
Size ~ 2nm



A. Zani *et al.*, Carbon, 56 358 (2013)

Role of process parameters - pressure



Tuning a single parameter may not be enough….

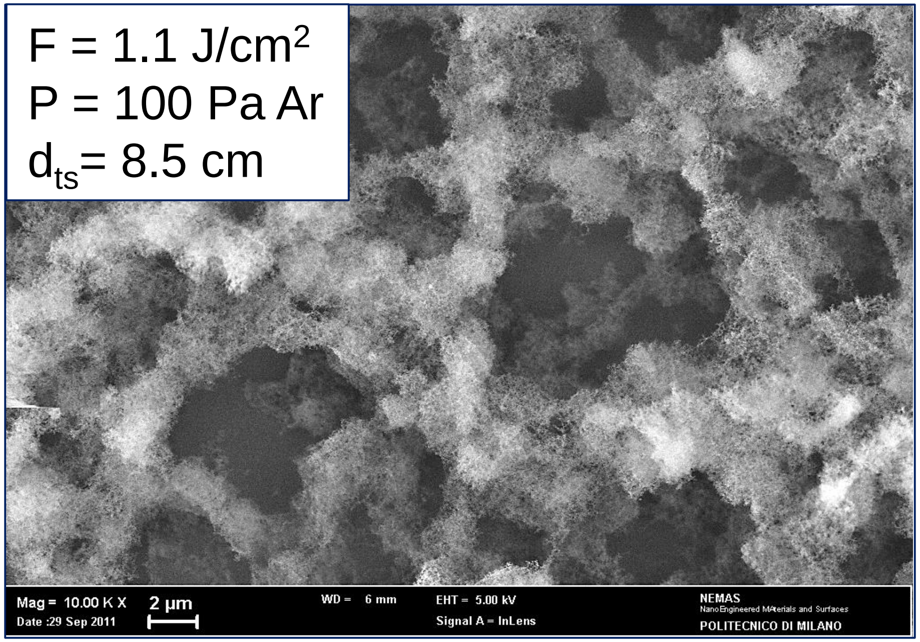
Same density = 1.5 n_c

Same thickness ≈ 8 µm

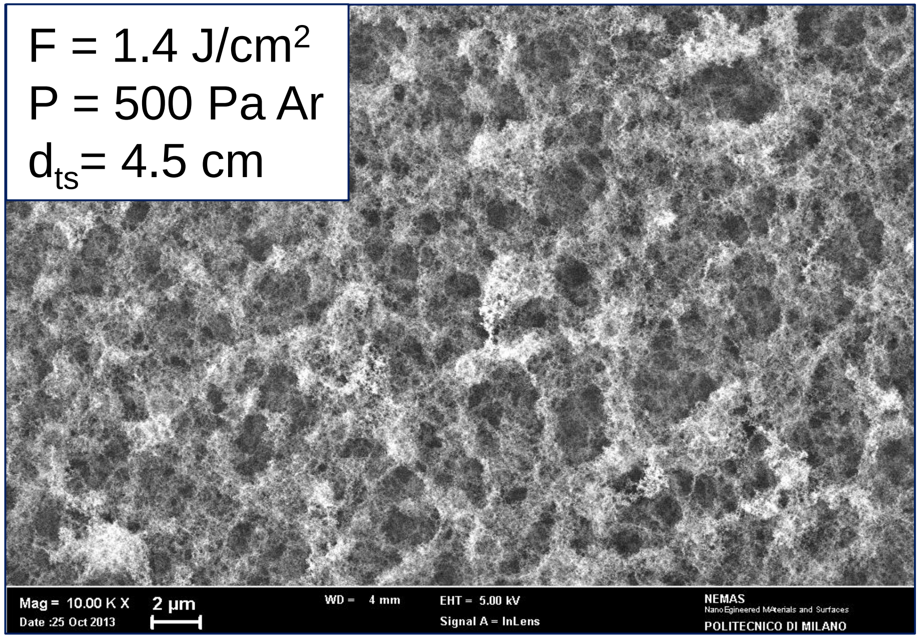
2011

2013

F = 1.1 J/cm^2
P = 100 Pa Ar
d_{ts}= 8.5 cm



F = 1.4 J/cm^2
P = 500 Pa Ar
d_{ts}= 4.5 cm



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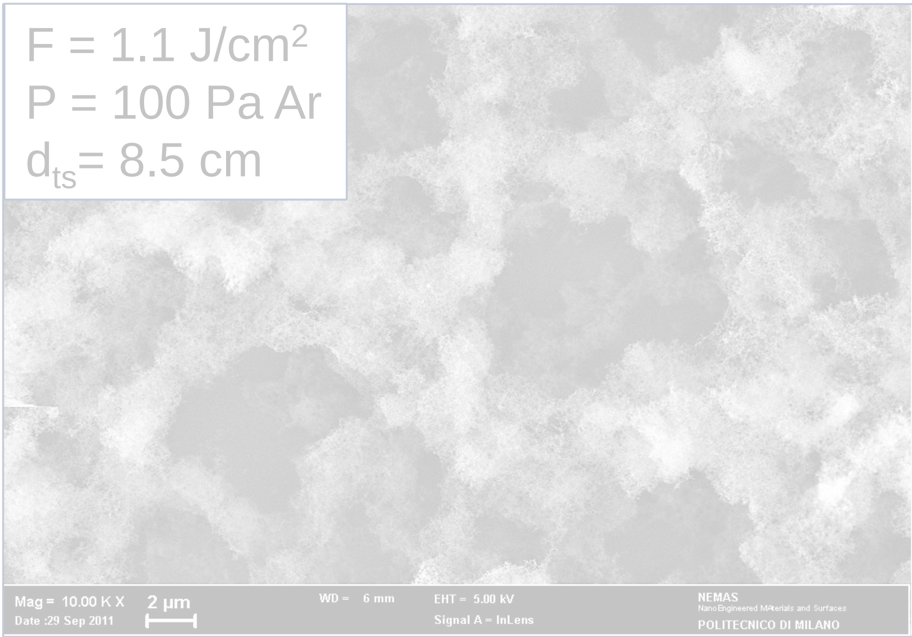

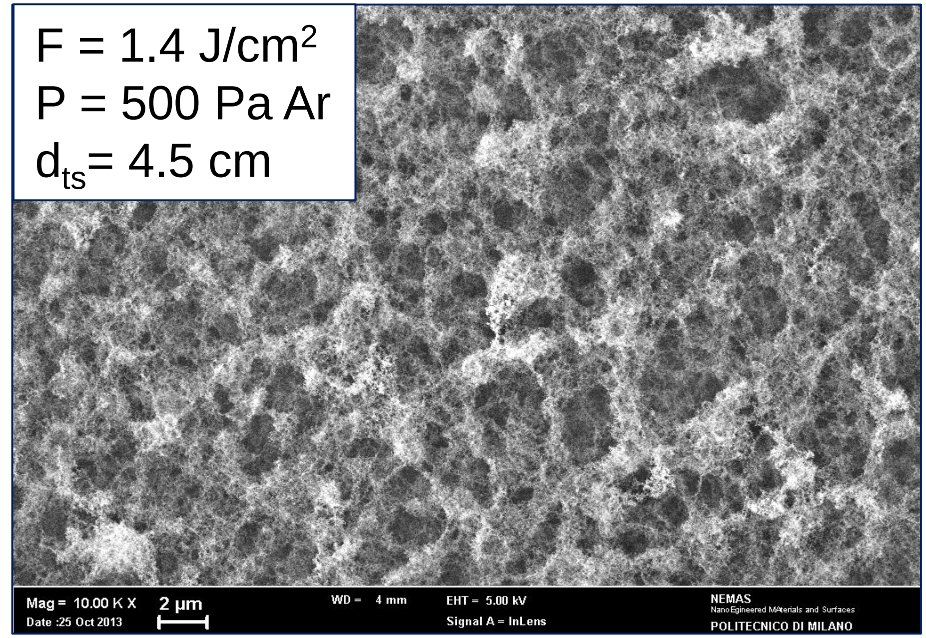

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Better uniformity & coverage!

Towards “thinner” foams…

0^{th} order solution: decreasing deposition time

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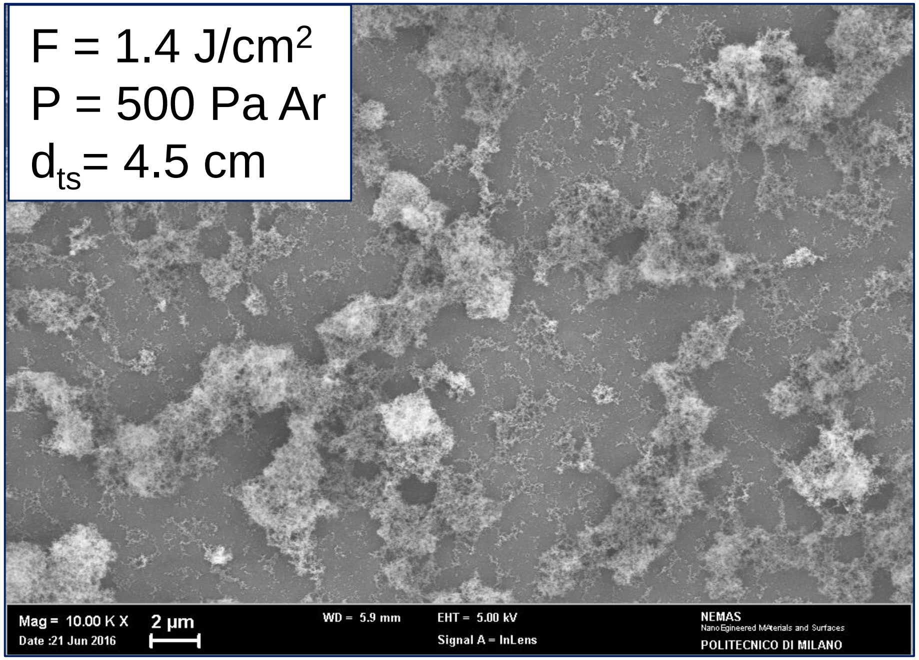

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Towards "thinner" foams…

0th order solution: decreasing deposition time

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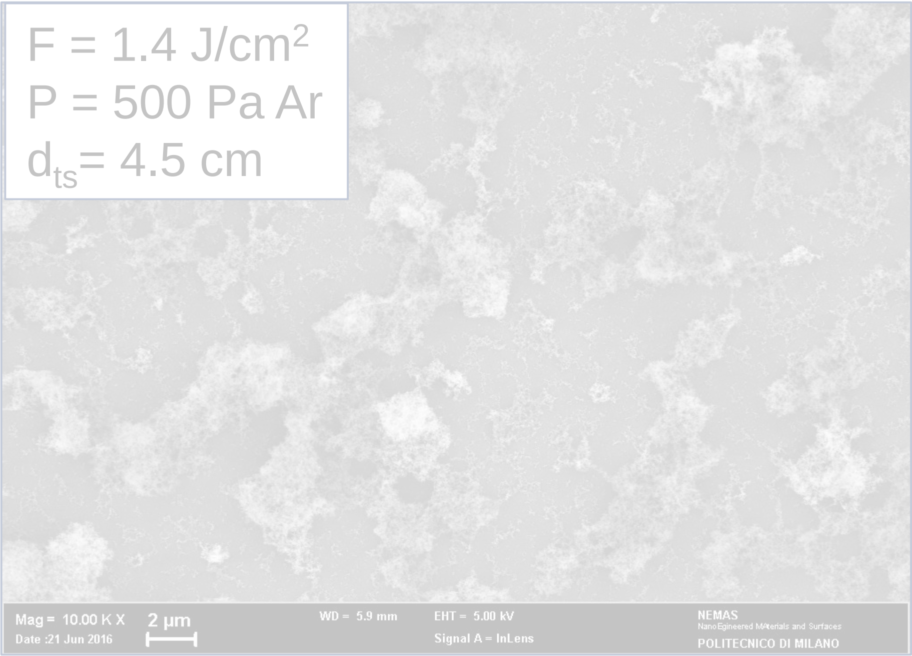

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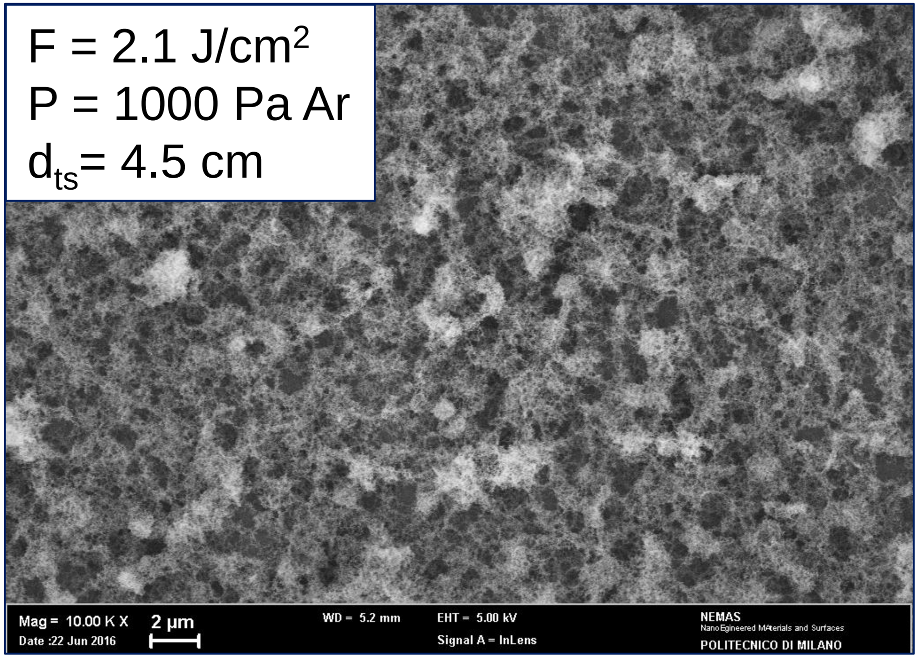


1) Decreasing deposition time might not be enough…

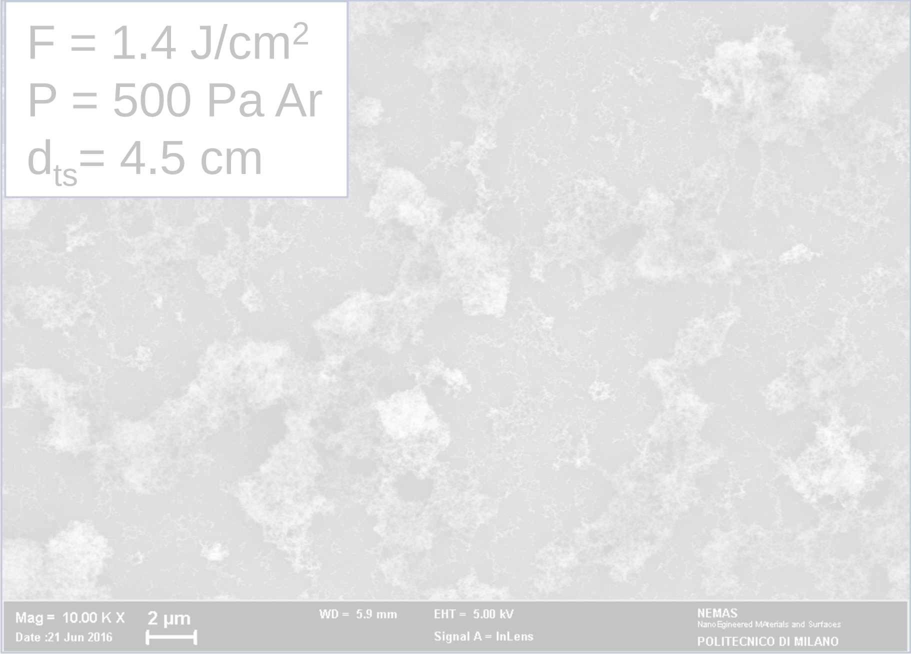
2) ↑ Fluence & ↑ Background pressure!

Towards "thinner" foams…

0^{th} order solution: decreasing deposition time

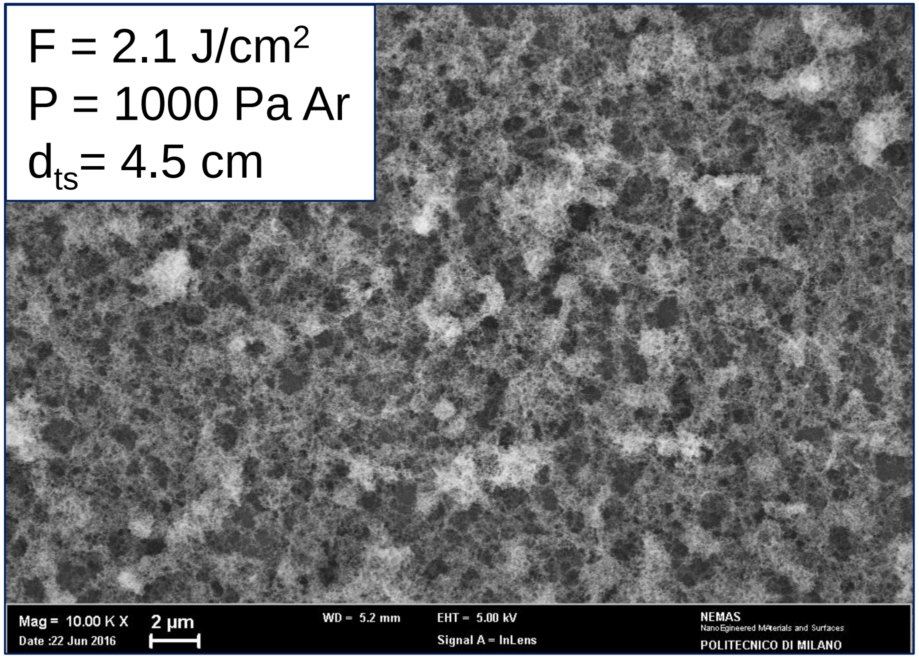
Nominal thickness ≈ 4 µm

F = 1.4 J/cm^2
P = 500 Pa Ar
d_{ts}= 4.5 cm



Nominal thickness ≈ 4 µm

F = 2.1 J/cm^2
P = 1000 Pa Ar
d_{ts}= 4.5 cm

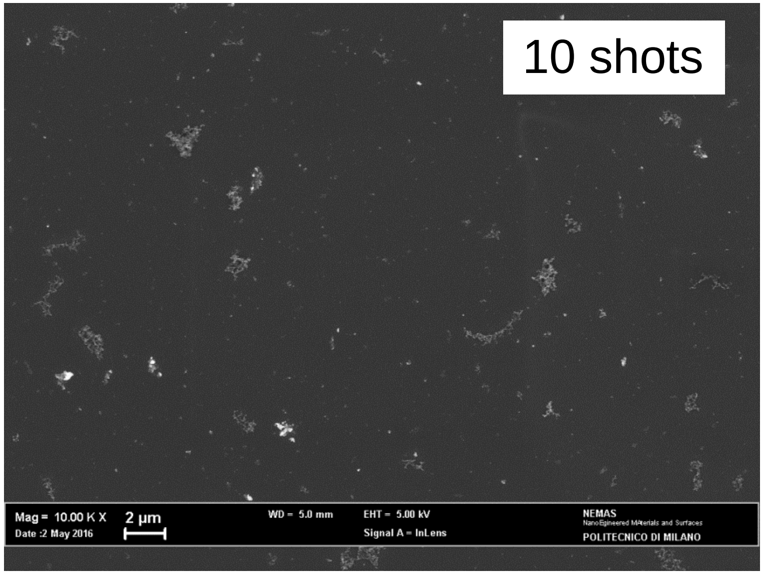


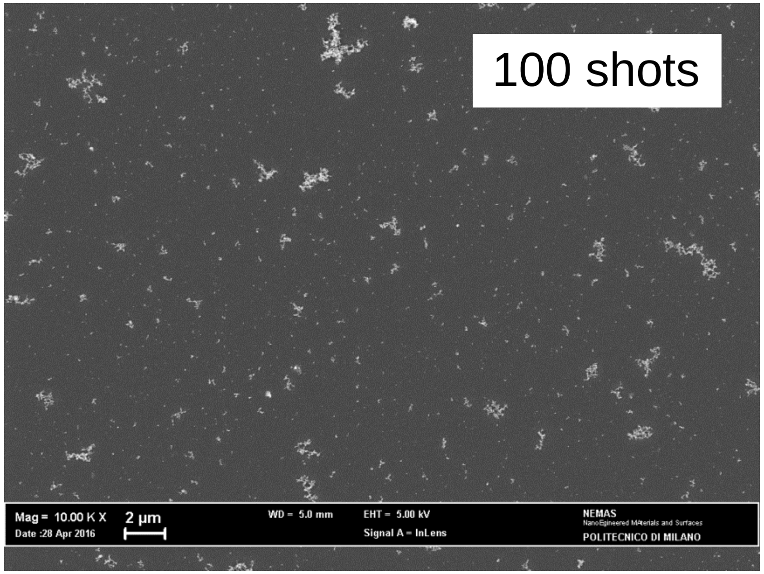
1) Decreasing deposition time might not be enough…

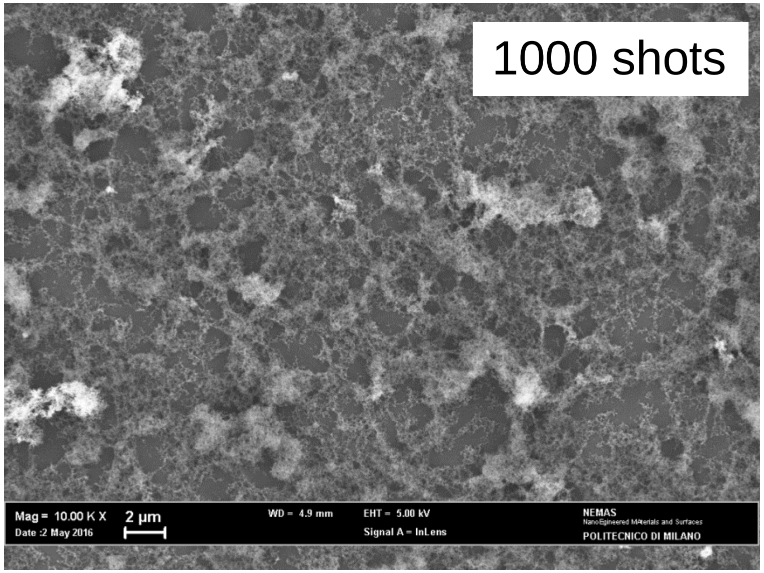
2) ↑ Fluence & ↑ Background pressure!

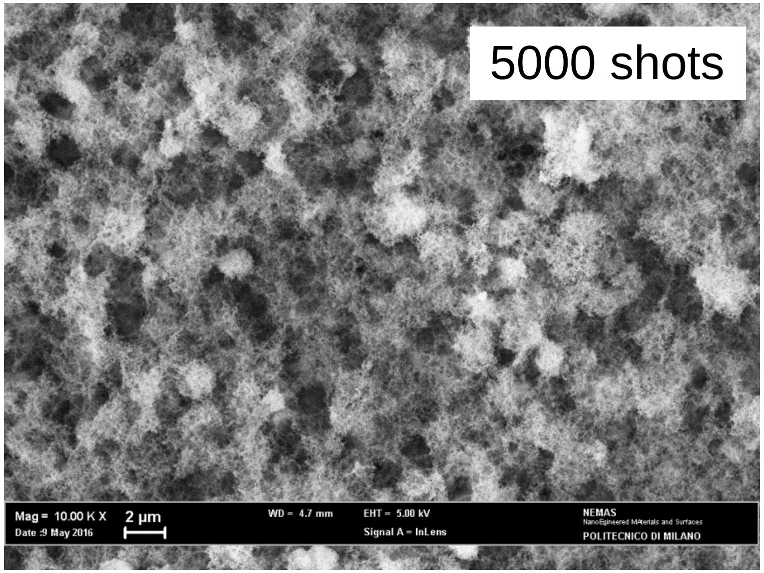
3) How does the foam grow?

Observing the foam growth process….





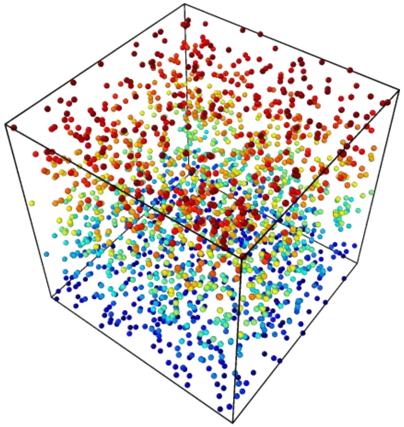




…And trying to model it!

Diffusion Limited Cluster-Cluster Aggregation (DLCA)

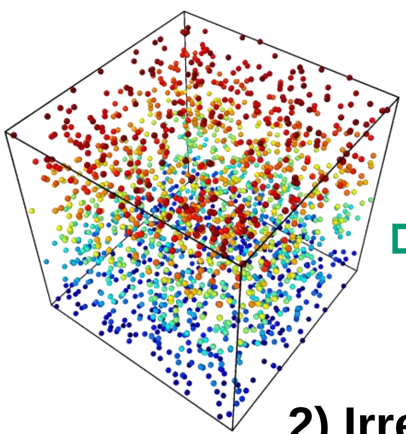
1) Brownian motion of nanoparticles (15 nm)



…And trying to model it!

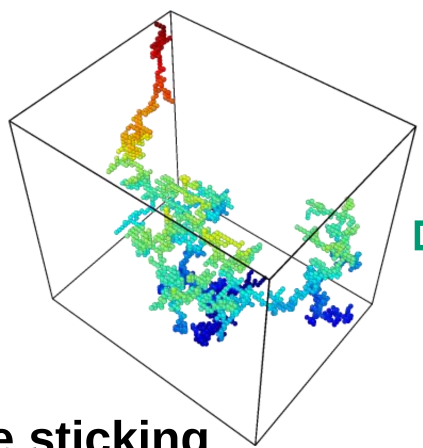
Diffusion Limited Cluster-Cluster Aggregation (DLCA)

1) Brownian motion of nanoparticles (15 nm)



2) Irreversible sticking of nanoparticles

3) Formation of clusters (10-1000 NPs)

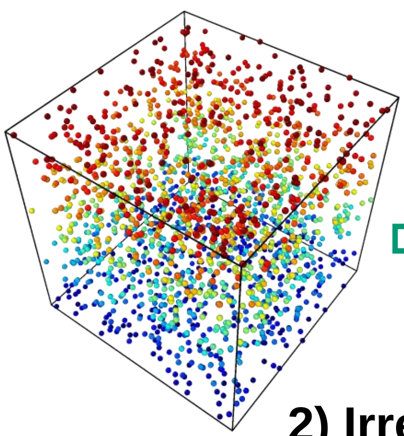


…And trying to model it!

Diffusion Limited Cluster-Cluster Aggregation (DLCA)

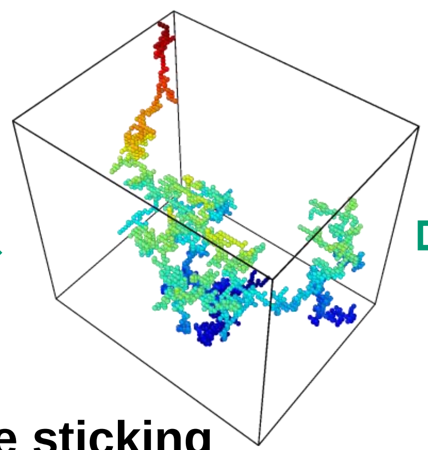
4) Deposition of clusters **on substrate**

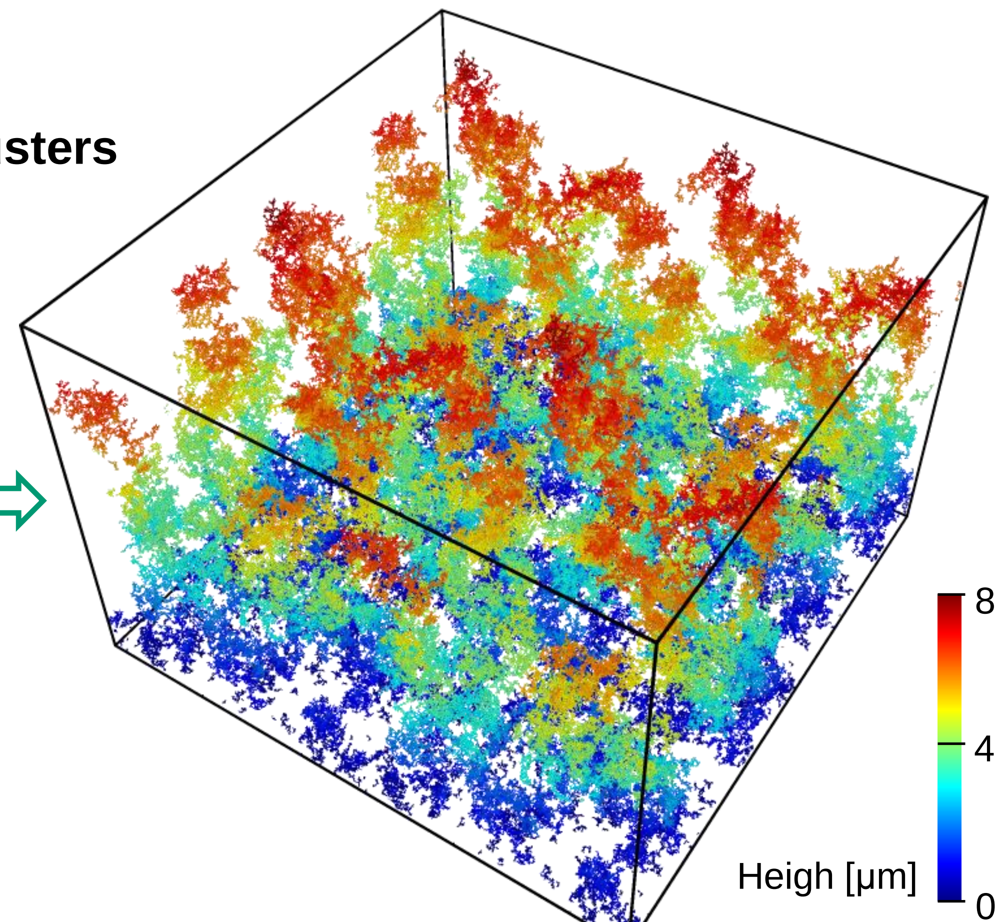
1) Brownian motion of nanoparticles (15 nm)



2) Irreversible sticking of nanoparticles

3) Formation of clusters (10-1000 NPs)

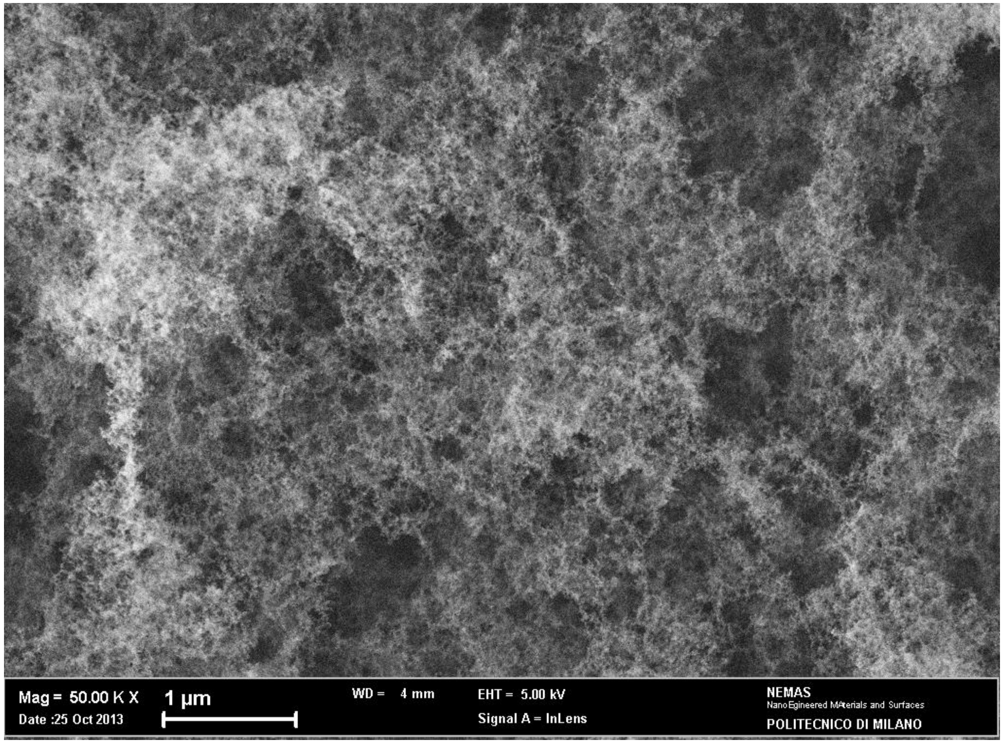




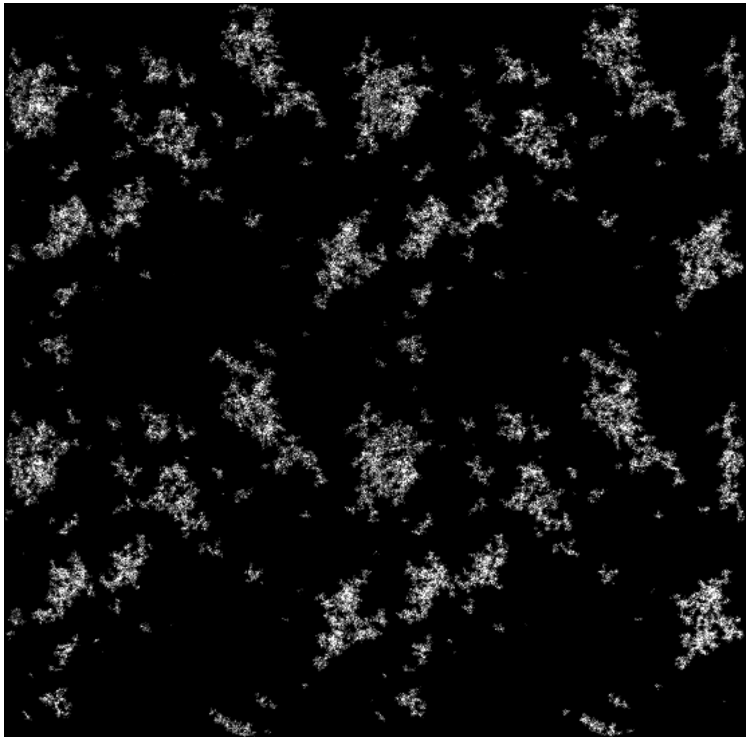
…And trying to model it!

Diffusion Limited Cluster-Cluster Aggregation (DLCA)

Real Foam



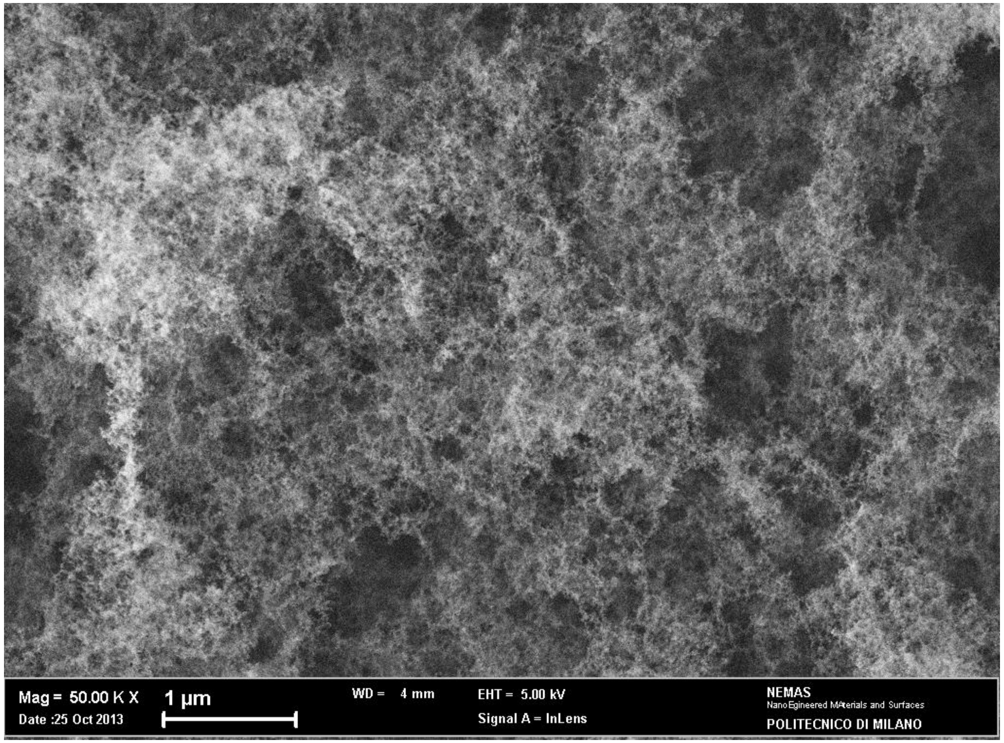
DLCA growth model



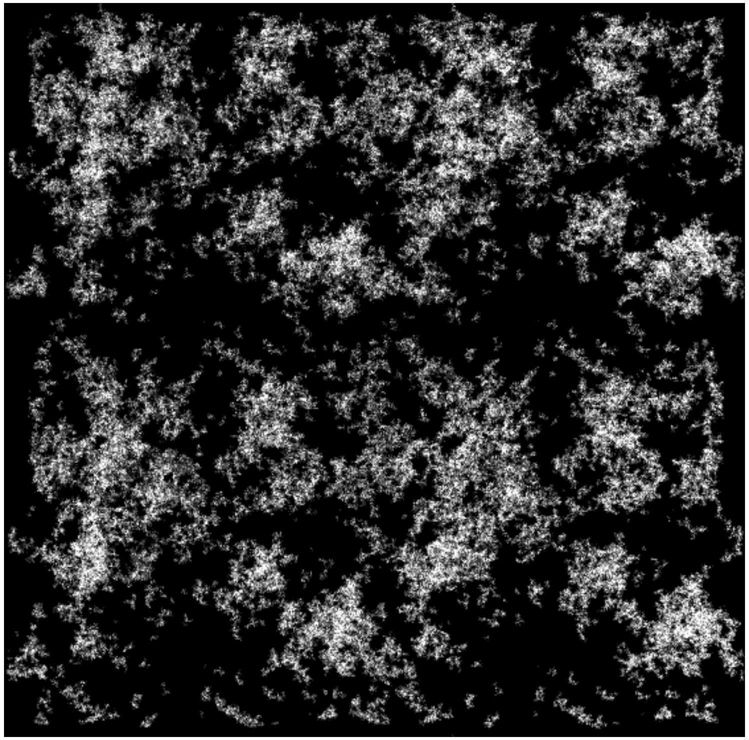
…And trying to model it!

Diffusion Limited Cluster-Cluster Aggregation (DLCA)

Real Foam



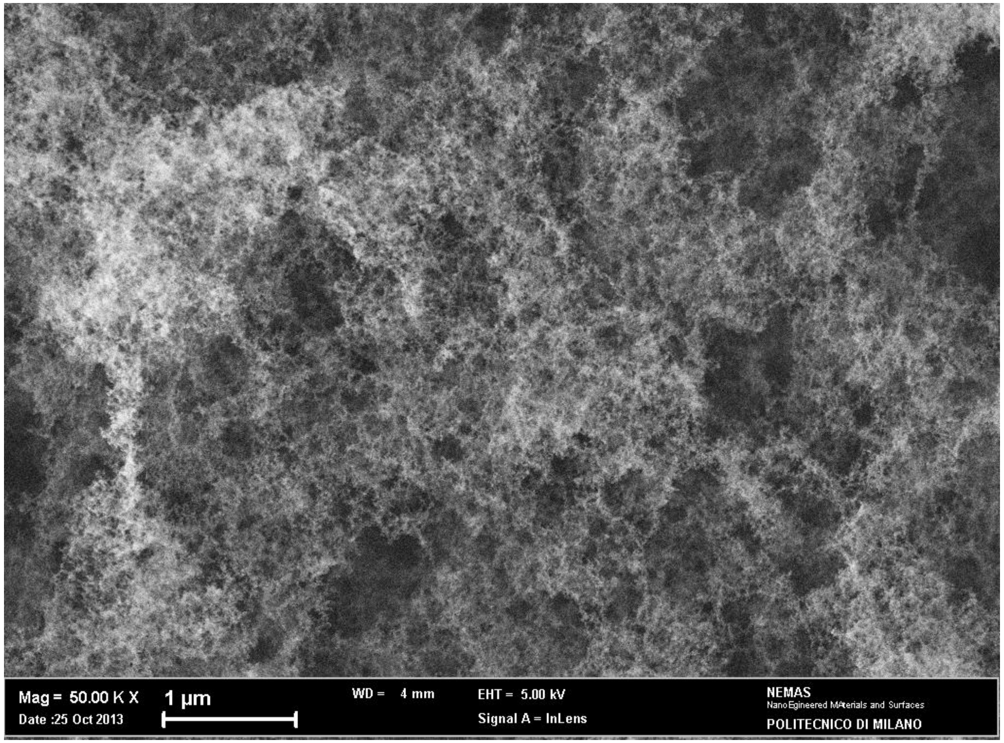
DLCA growth model



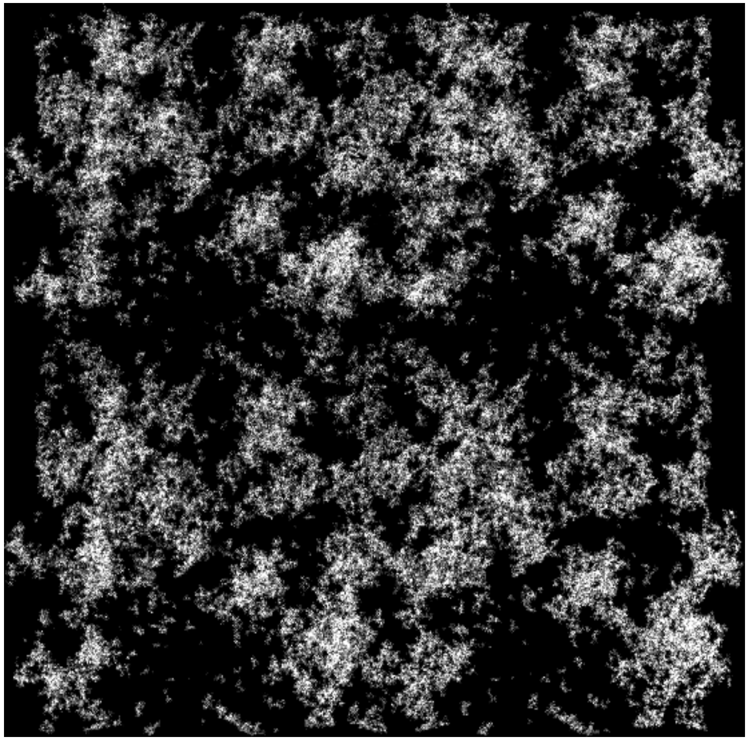
…And trying to model it!

Diffusion Limited Cluster-Cluster Aggregation (DLCA)

Real Foam



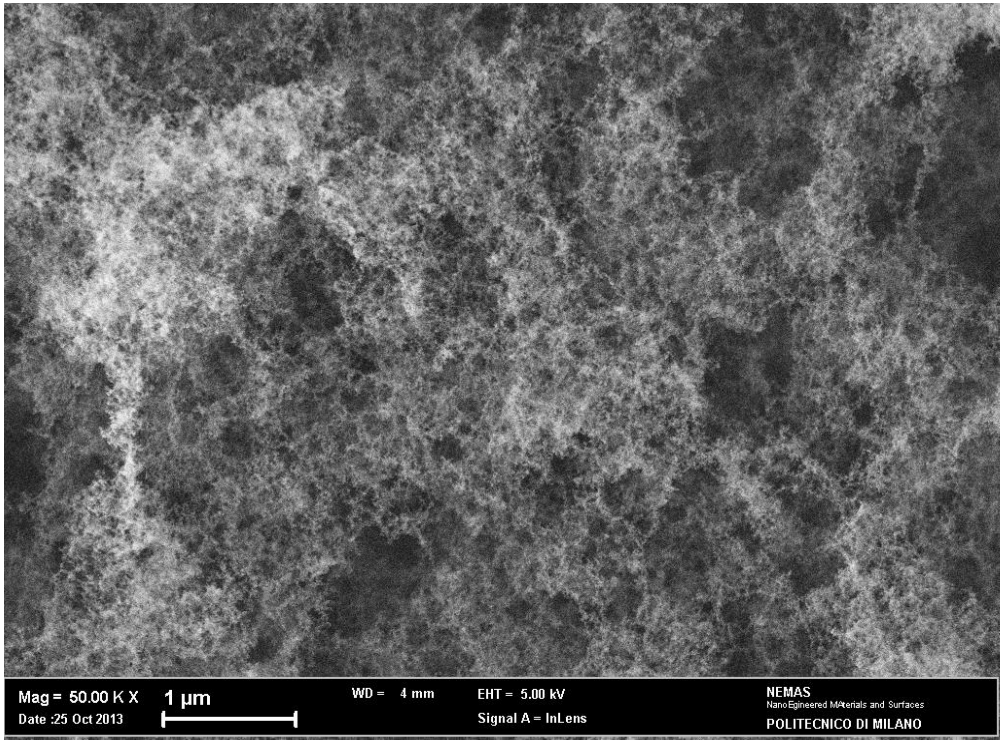
DLCA growth model



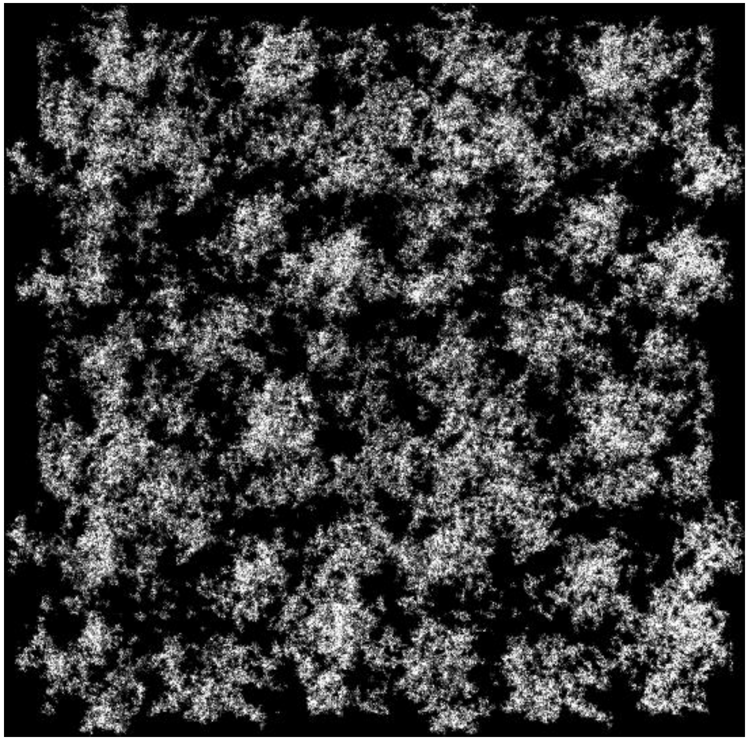
…And trying to model it!

Diffusion Limited Cluster-Cluster Aggregation (DLCA)

Real Foam



DLCA growth model



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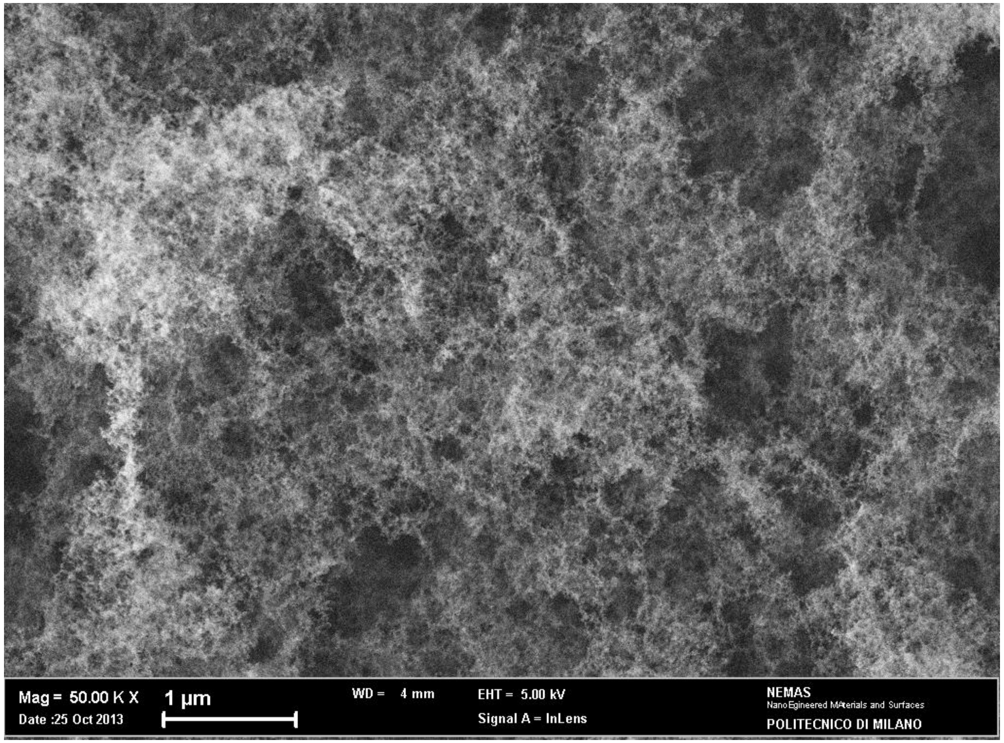
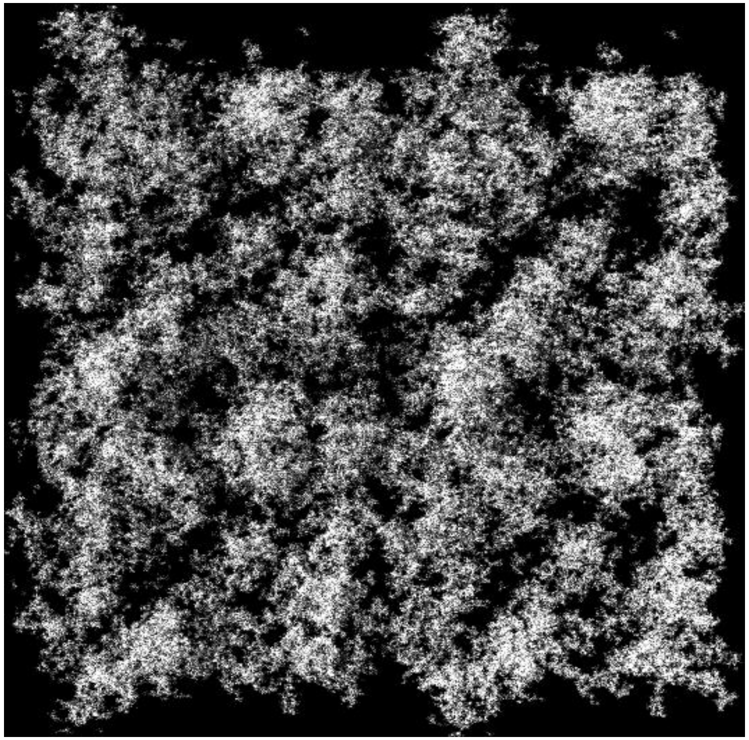
Diffusion Limited Cluster-Cluster Aggregation (DLCA)

Real Foam



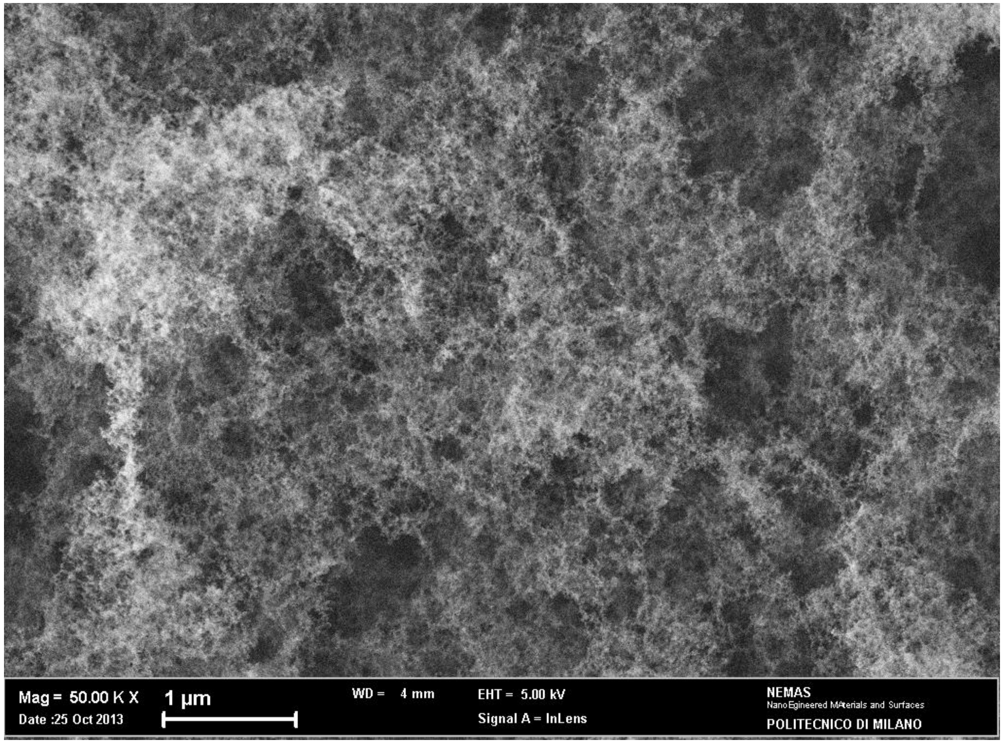
DLCA growth model



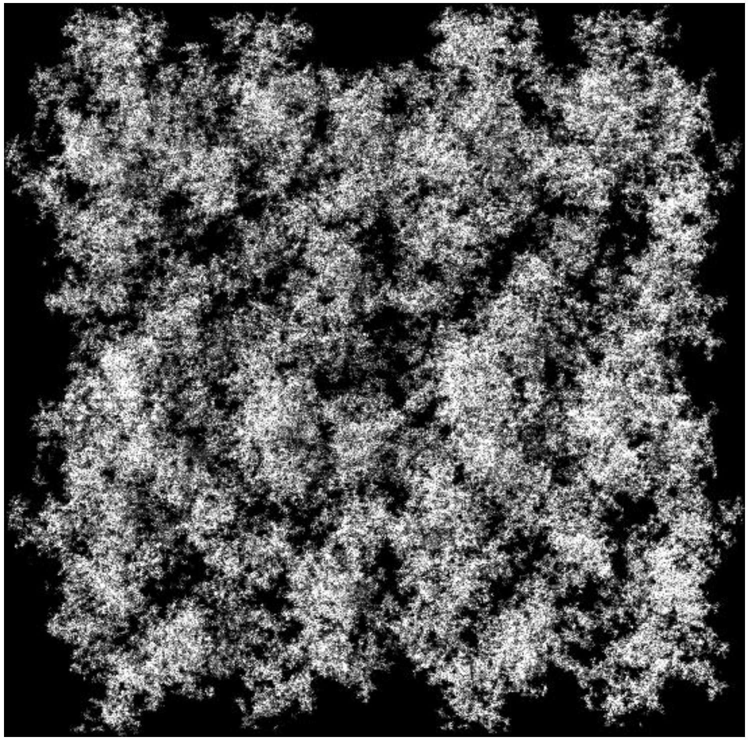
…And trying to model it!

Diffusion Limited Cluster-Cluster Aggregation (DLCA)

Real Foam



DLCA growth model



Laser-driven acceleration experiments with foams

2014/2015: enhanced TNSA

May 2017: ion acceleration & physics of irradiated near-critical plasmas

2017/2018: collision-less shocks & ps laser interaction with nanostructured foams

2017/2018 : pulsed neutron generation

ERC-PoC: INTER

2017/2018 : compact ion and neutron sources for materials characterization

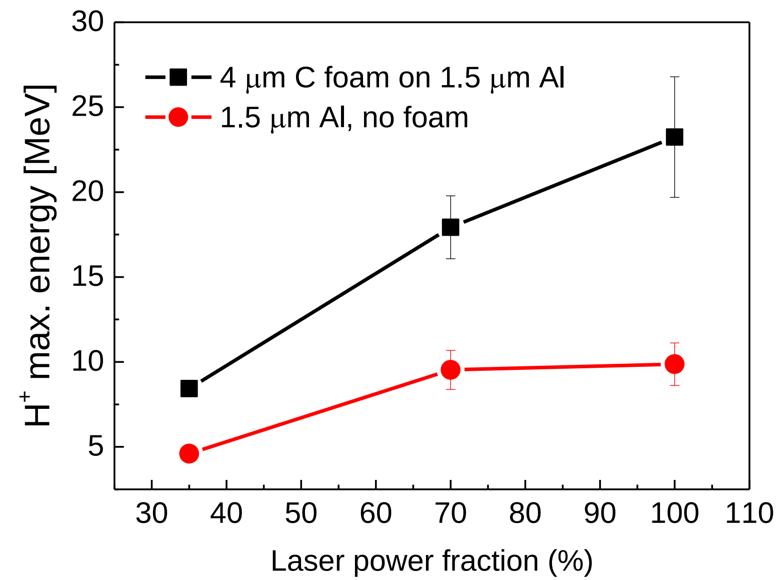
M. Passoni et al., *Plasma Phys. Control. Fusion* **56** (2014) 045001
I. Prencipe et al., *Plasma Phys. Control. Fusion* **58** (2016) 034019
M. Passoni et al., *Phys. Rev. Accel. Beams* **19**, (2016) 061301

Ion acceleration @ DRACO 150 TW (preliminary data!)

in collaboration with:
I. Prencipe, T. Cowan, U. Schram et al.

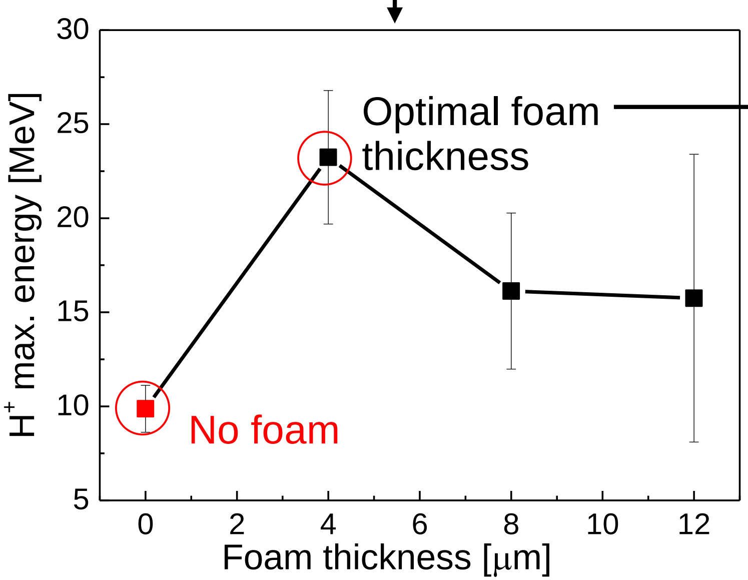
Laser parameters @ Draco (HZDR, Dresden)

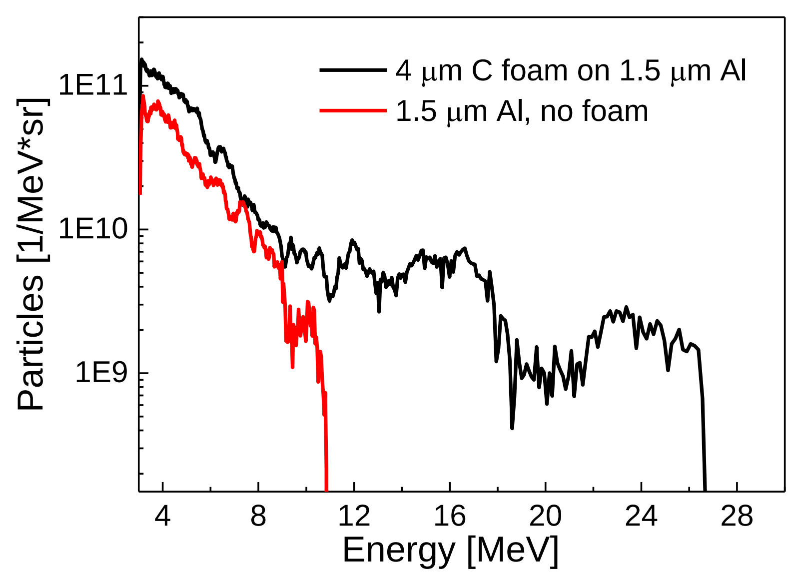
- Energy on target = 2 J
- Intensity = up to 5 x 10^{20} W/cm^2
- Angle of incidence = 2°



Foam PLD parameters

- F = 2.1 J/cm^2
- P = 1000 Pa Ar
- d_{ts}= 4.5 cm
- Substrate = Al 1.5 μm
- Foam thickness = 4, 8, 12 μm





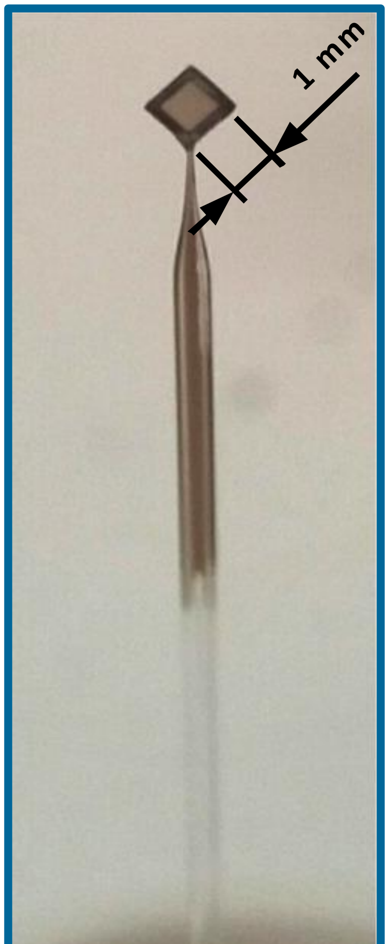
Next steps: advanced target development

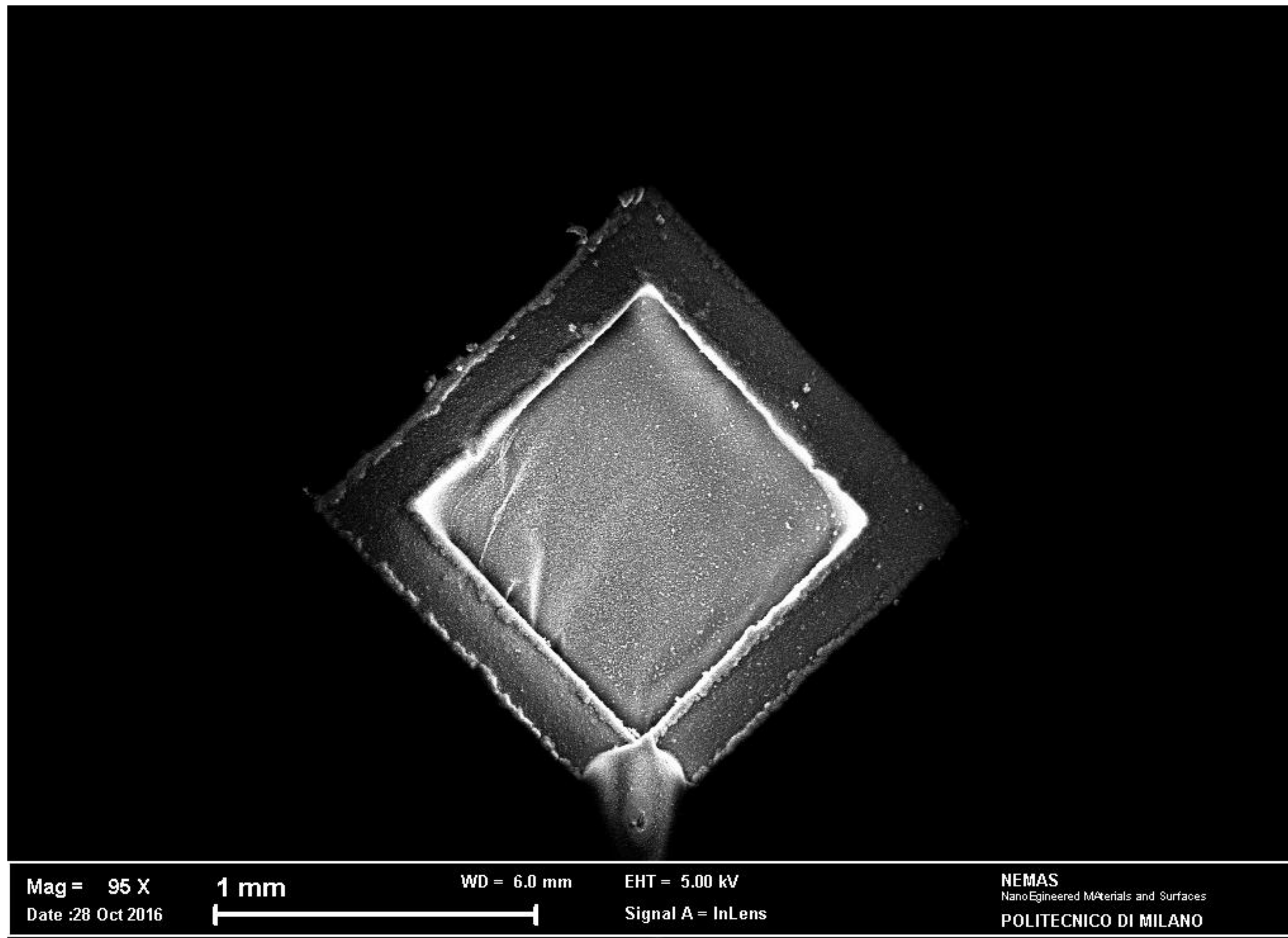
in collaboration with: A. Morace

OSAKA UNIVERSITY

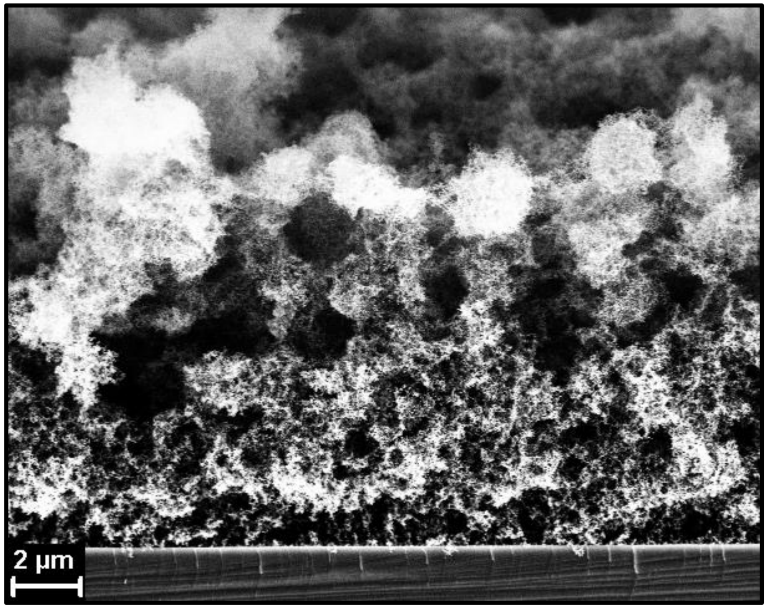
Double side deposition on a ultra-thin CH layer (100 nm)

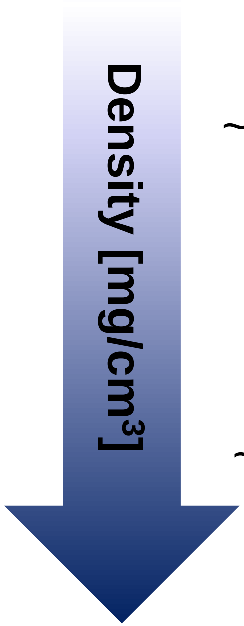
Interest: laser induced electrostatic shock generation





Next steps: functionally graded foams

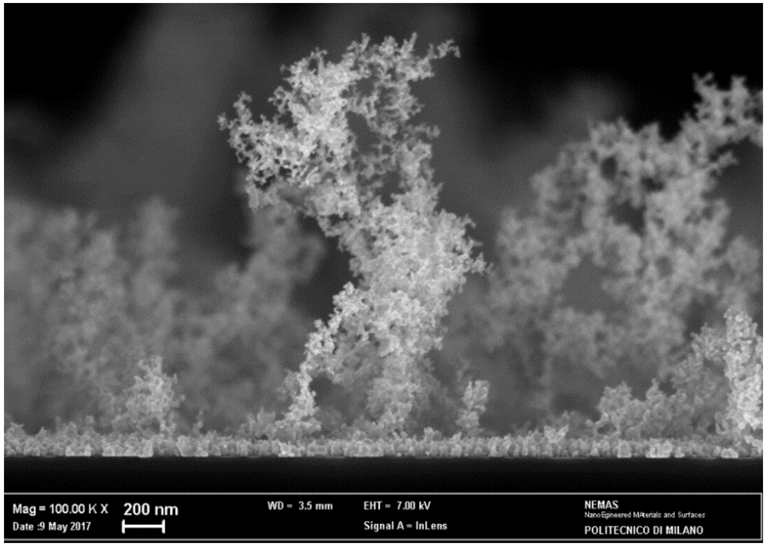




~10 mg/cm^3

~150 mg/cm^3

Next steps: metallic and CH foams



Gold Foam: PLD parameters

- E=100 mJ
- P=1000 Pa Ar
- d_{ts}= 5 cm

Courtesy of L. Mascaretti

Next steps: fs-PLD under development

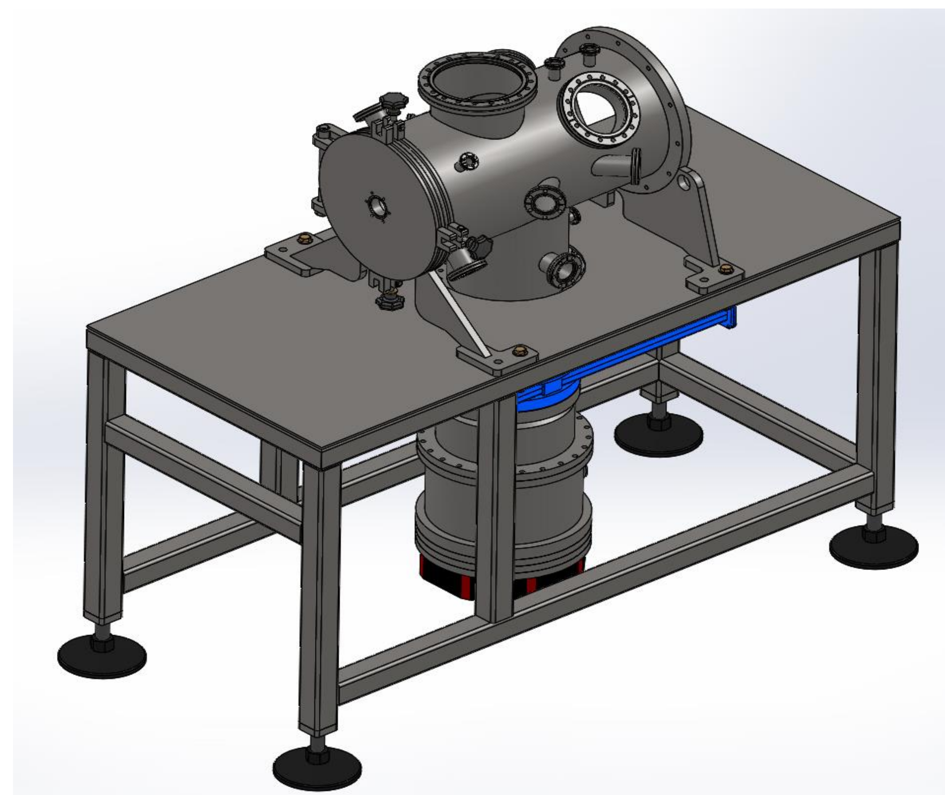
<u>Coherent “Astrella”</u>

- Tabletop laser
- τ < 100 fs
- E_p > 5 mJ

➢ Femto-machining and laser processing

➢ **<u>Femtosecond PLD</u>**

- inherent production of NPs
- New frontiers in foam production?



Acknowledgment

The "ENSURE" team

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M. Passoni


V. Russo


M. Zavelani-Rossi


D. Dellasega


A. Maffini


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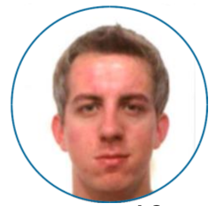
L. Cialfi


A. Formenti


A. Pazzaglia


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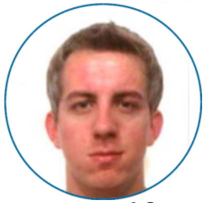
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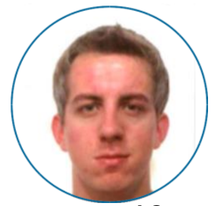
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....Thank you for your attention!

More info on our website

www.ensure.polimi.it