POLITECNICO DI MILANO

Production of low density targets for laser driven ion acceleration

I. Prencipe[1], A. Zani[1], D. Dellasega[1], V. Russo[1], T. Ceccotti[2], V. Floquet[2], A. Sgattoni[1,3], A. Macchi[1,4], M. Passoni[1]

[1]Dipartimento di Energia and NEMAS, Politecnico di Milano, Milano, Italy
[2]CEA, IRAMIS, SPAM, F-91191 Gif-sur-Yvette, France
[3]Consiglio Nazionale delle Ricerche, Istituto Nazionale di Ottica (CNR/INO), Pisa, Italy
[4]Dipartimento di Fisica, Università di Pisa, Pisa, Italy

irene.prencipe@polimi.it

Overview

INTRODUCTION

- LASER-PLASMA INTERACTION IN NEAR-CRITICAL REGIME
- LOW DENSITY TARGETS FOR LASER DRIVEN ION ACCELERATION

CARBON FOAMS: PRODUCTION AND CHARACTERIZATION

- PULSED LASER DEPOSITION (PLD)
- MORPHOLOGICAL AND NANOSCALE ANALYSIS
- DENSITY MEASUREMENT

ACCELERATION EXPERIMENTS

- MULTI-LAYERED TARGETS

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Laser-plasma interaction in near-critical regime

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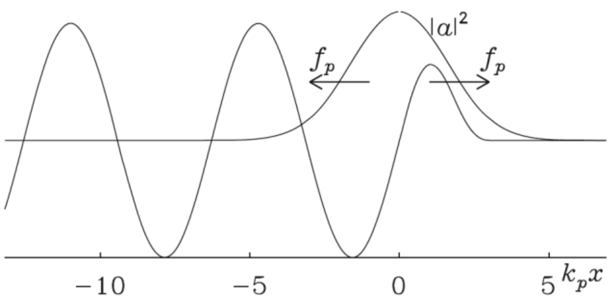
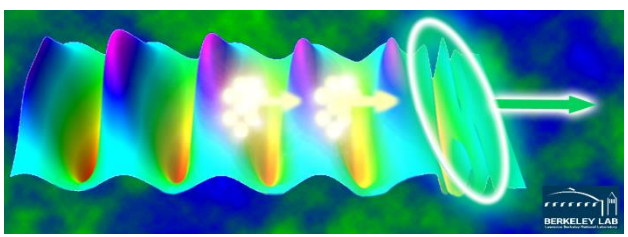
CRITICAL DENSITY $n_c = \frac{m_e \omega^2}{4\pi e^2}$ ➡ $\rho_c \approx mg/cm^3$ for $\lambda \cong 1\ \mu m$

$n < n_c$ UNDER-DENSE PLASMA

EM waves propagation in plasma allowed: volume interaction mechanisms

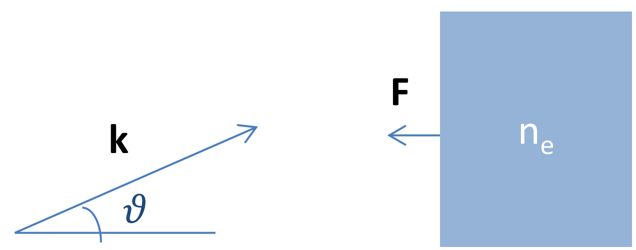




Electron acceleration via wavebreaking

$n > n_c$ OVER-DENSE PLASMA

EM waves propagation only in a skin layer: surface interaction mechanisms



Vacuum heating

$$F = -2eE_L \sin(\vartheta)$$

J × B heating

$$F = F_{PM,\,DC} + f(x)\cos(2\omega t)$$

if s-polarized wave or normal incidence

P. Gibbon, Short Pulse Laser Interaction with Matter, Imperial College Press, (2005)
A. Macchi, A Superintense Laser–Plasma Interaction Theory Primer, Springer (2013)

Laser-plasma interaction in near-critical regime

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$n < n_c$ **UNDER-DENSE PLASMA**

EM waves propagation in plasma allowed:
volume interaction mechanisms

$n > n_c$ **OVER-DENSE PLASMA**

EM waves propagation only in a skin layer:
surface interaction mechanisms

$n \approx n_c$ **NEAR-CRITICAL PLASMA**

- ✓ volume and surface interaction mechanisms
- ✓ higher absorption efficiency
- ✓ enhanced generation of hot electrons

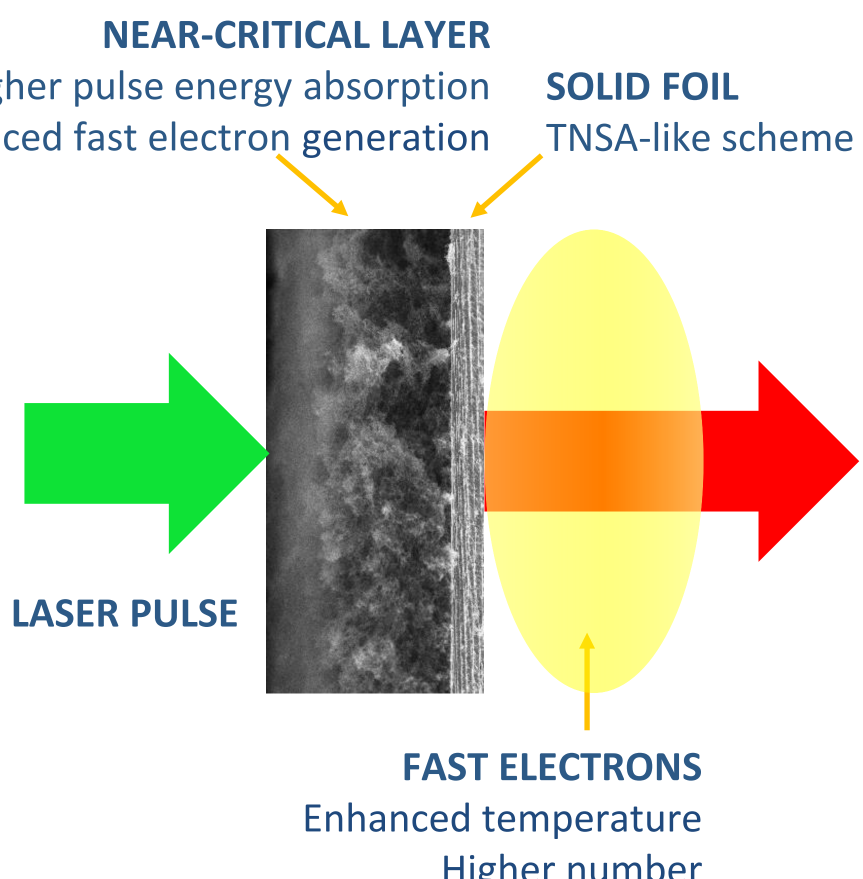
L. Willingale et al. *Phys. Rev. Lett* **96**, 245002 (2006); **102**, 125002 (2009)
S. S. Bulanov et al. *Phys. Plasmas* **17**, 044105 (2010)

Enhanced Target Normal Sheath Acceleration

GOAL → Enhancement of maximum ion energy

STRATEGY → Enhancement of laser energy absorption through proper **TARGET DESIGN**

Multi-layered targets



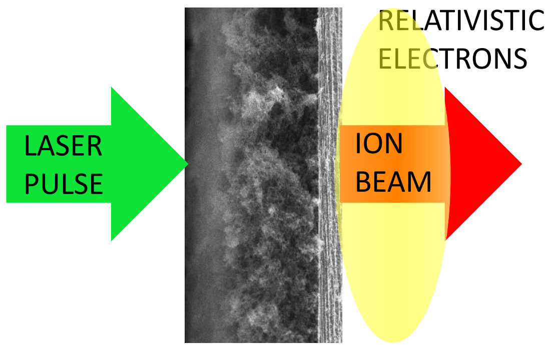
ACCELERATED IONS

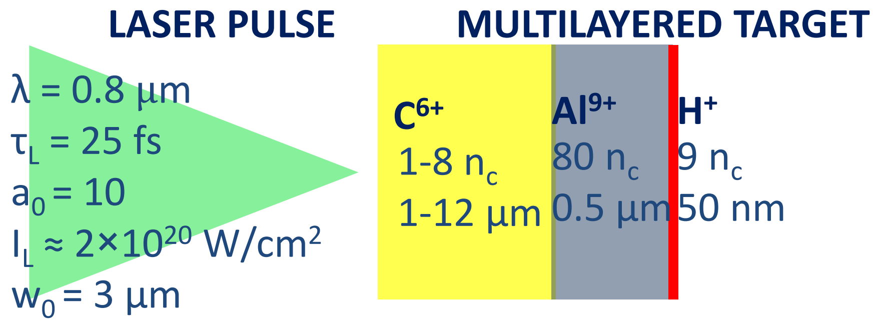
- Increased maximum ion energy
- MeV ions even with moderate intensities (10^{16} W/cm^2)

T. Nakamura *et al.*, Phys. Plasmas, **17** 113107 (2010)
A. Sgattoni *et al.*, Phys. Rev. E, **85** 036405 (2012)

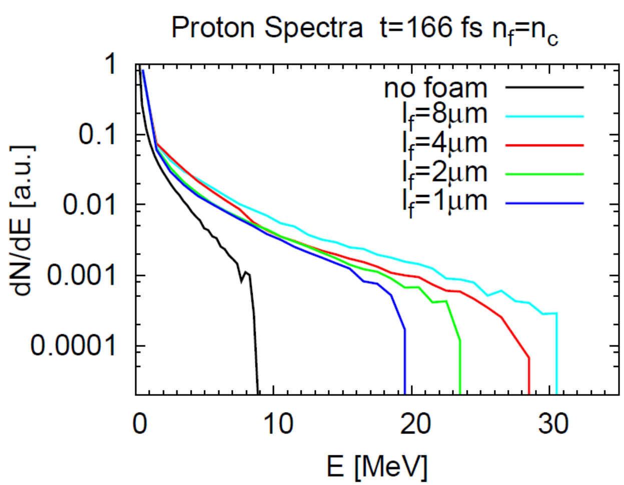
Enhanced Target Normal Sheath Acceleration

Multi-layered targets: 2D PIC simulations ALaDyn code

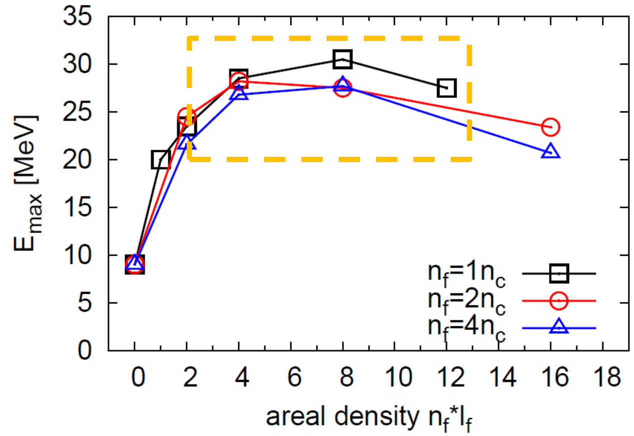




ENHANCED MAXIMUM PROTON ENERGY FOR FOAM-ATTACHED TARGETS



OPTIMAL THICKNESS RANGE FOR GIVEN FOAM DENSITY AND LASER PARAMETERS



i.e. 10 μm for n_c and λ=0.8 μm

A. Sgattoni *et al.*, Phys. Rev. E, **85** 036405 (2012)

for further information see also A. Sgattoni's talk!

Other acceleration regimes

Hole Boring Radiation Pressure Acceleration

- **Laser piston**: over-critical plasma
- **Velocity scaling**

  non relativistic limit $v_{HB} \sim n_e^{-1/2} \Rightarrow \varepsilon_{max} \sim n_e^{-1}$

  ultrarelativistic limit $v_{HB} \approx c \Rightarrow \varepsilon_{max} \sim n_e^{-1/2}$

→ slightly over-dense targets

Collisionless Shock Acceleration

- **Shock**: over-critical plasma

  shock wavefront velocity $v_{shock} \approx v_{HB}$
- **Velocity scaling**: $v_i = 2v_{shock}$
- **Ion reflection condition**:

  intensity threshold proportional to ion density

→ slightly over-dense targets

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

Main goals

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Production of variable density carbon foams

- indipendent control of density/thickness/uniformity
- good adhesion to a solid substrate

Characterization of low density carbon foams

- development of a reliable technique to measure very low density values

Employment of low density targets in acceleration experiments

- test on multi-layered targets for enhanced TNSA

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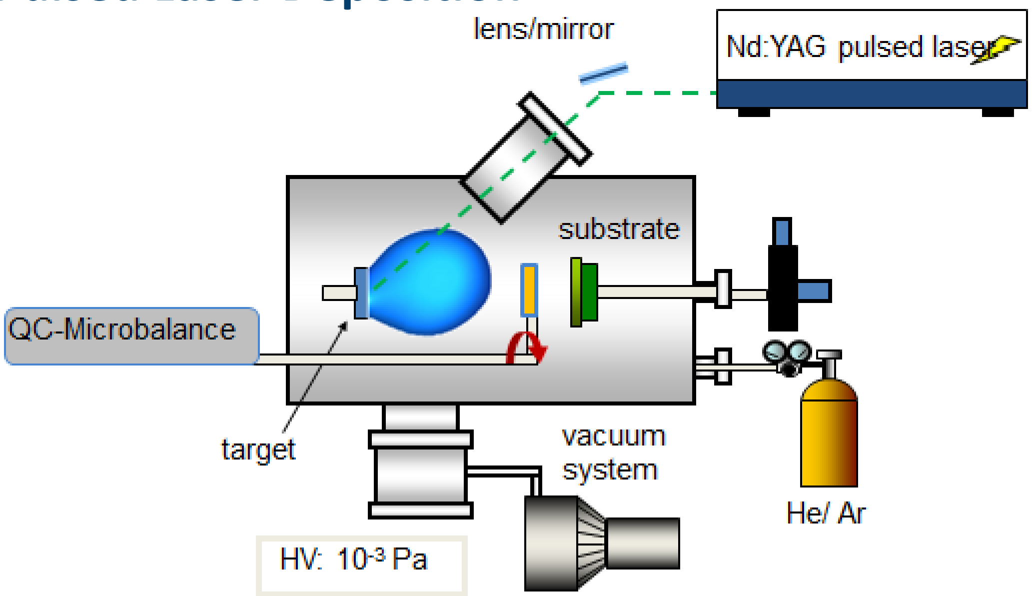
Production of carbon foams by PLD

Pulsed Laser Deposition



DEPOSITION PARAMETERS

Nd:Yag Laser (λ = 532 nm)

Fluence = 0,8 J cm^{-2}

$P_{Ar/He}$ = 0 – 1000 Pa

$d_{target-substrate}$ = 8.5 cm

TARGET

Pyrolitic graphite

SUBSTRATE

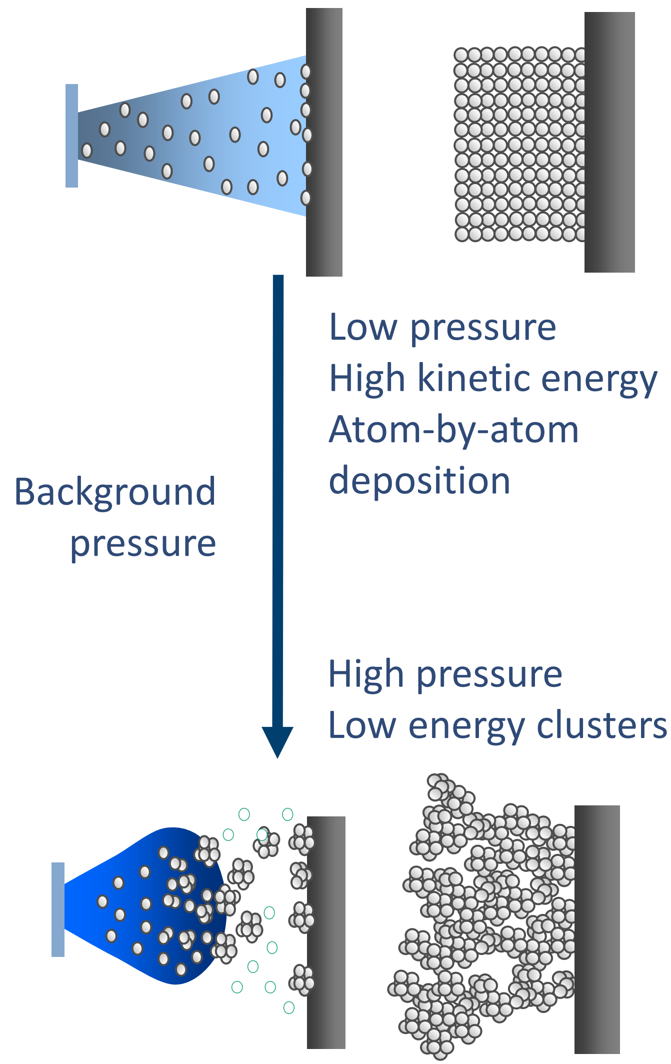
Si <100> for characterization

Al (0.7-12 μm) for E-TNSA tests

C (3 nm on TEM grids)

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

Role of gas pressure

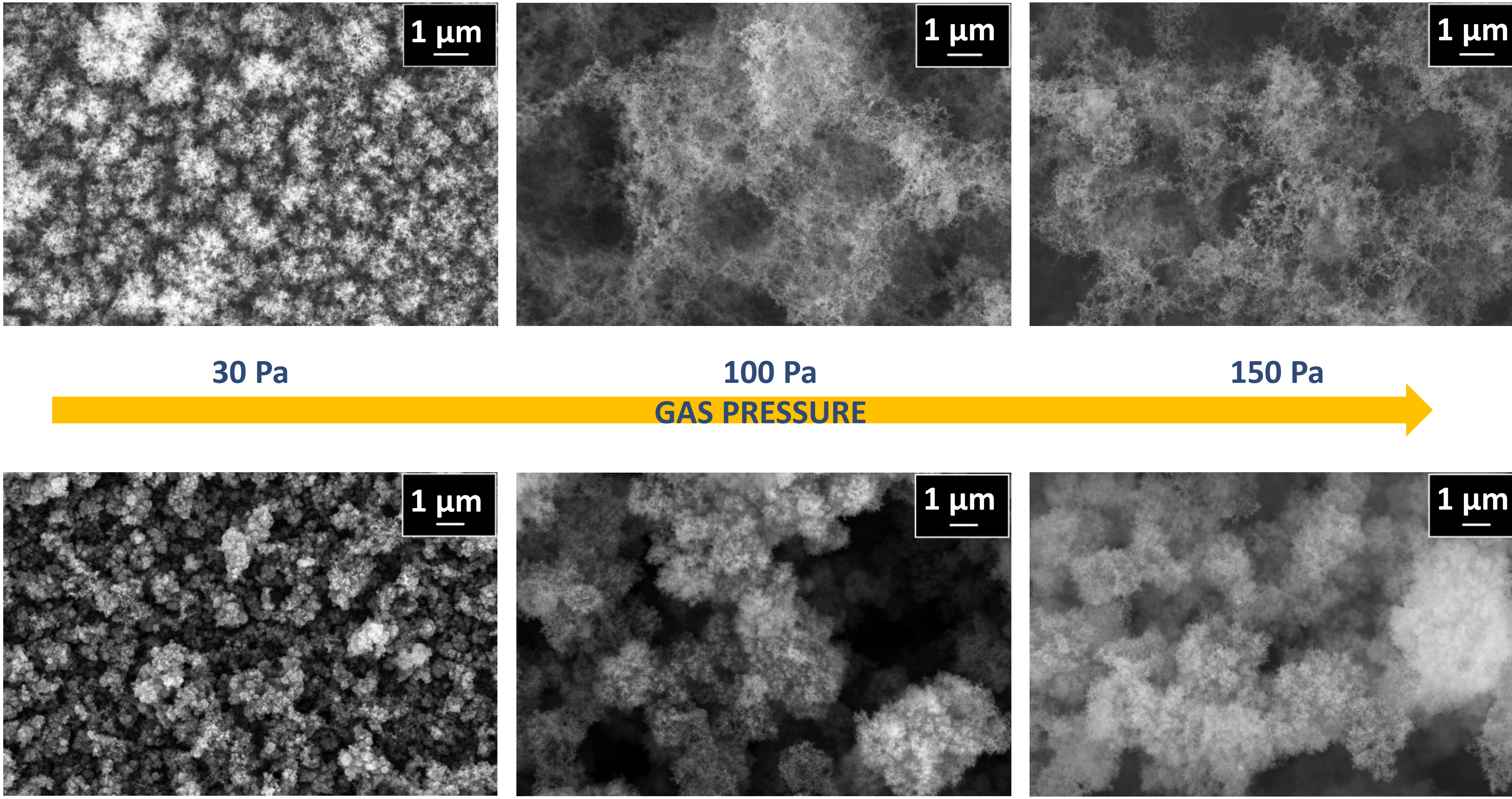


A. Bailini *et al.*, Appl. Surf. Sci., **253** 8130 (2007)

Morphological analysis

Scanning Electron Microscopy

Argon

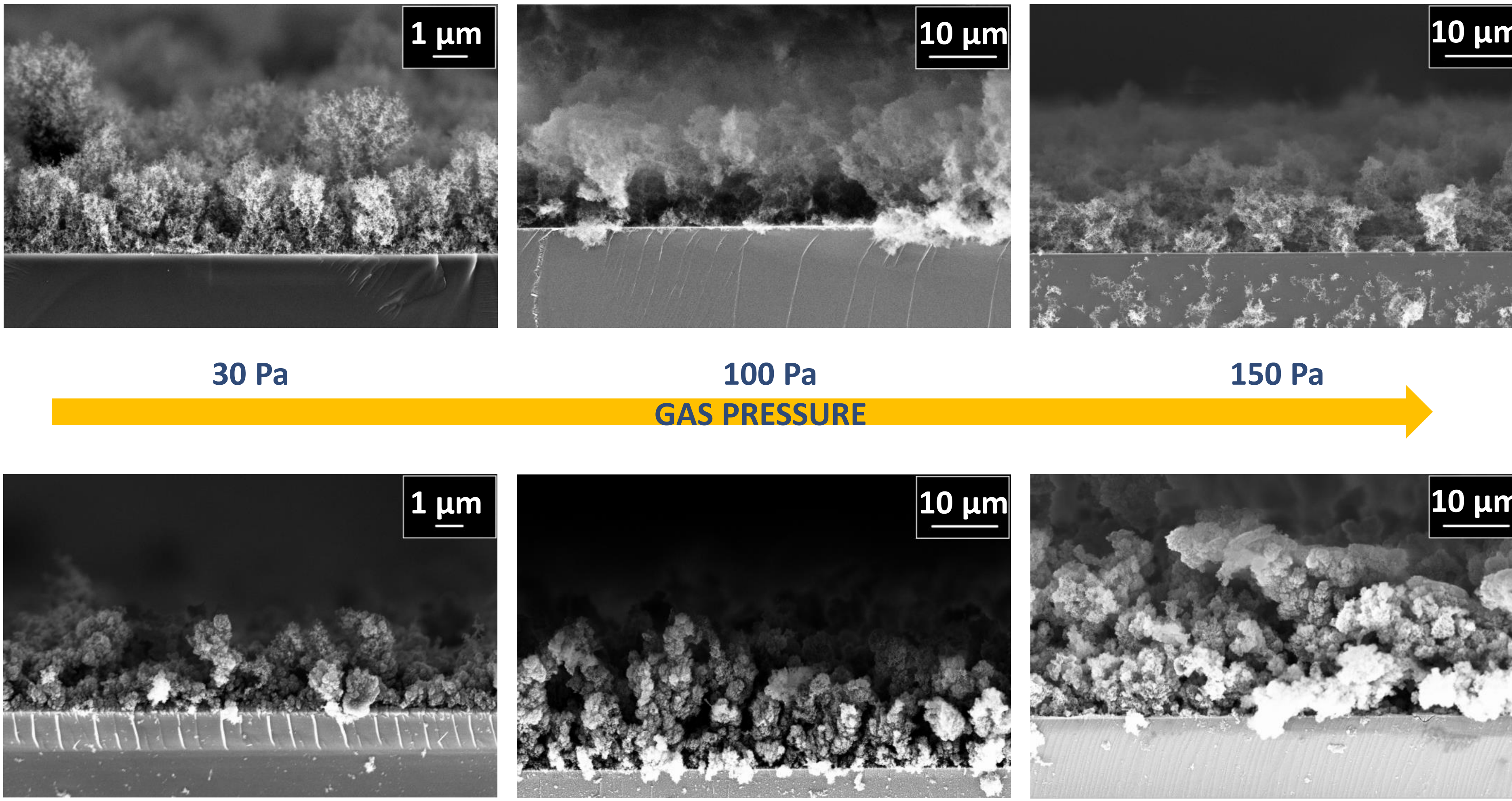


Helium

Morphological analysis

Scanning Electron Microscopy

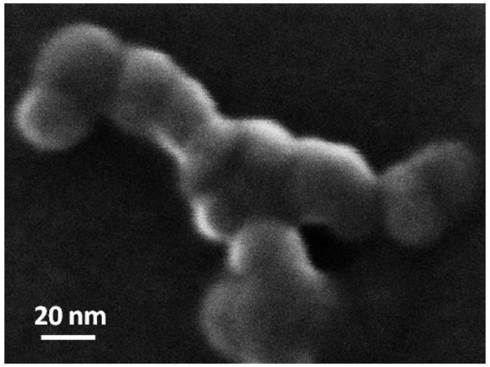
Argon



Helium

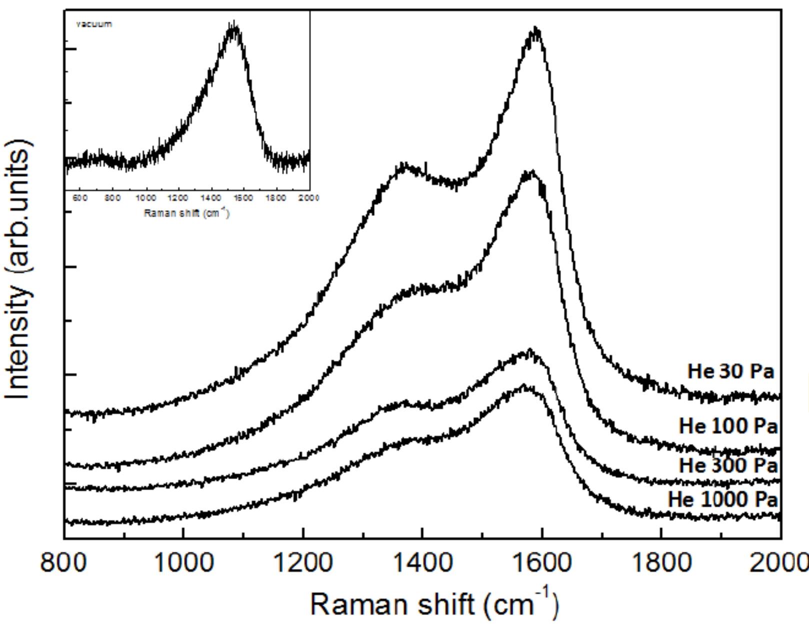
Nanoscale analysis

Scanning Transmission Electron Microscopy



- Elementary consituents:
  10-20 nm nanoparticles

Raman spectroscopy

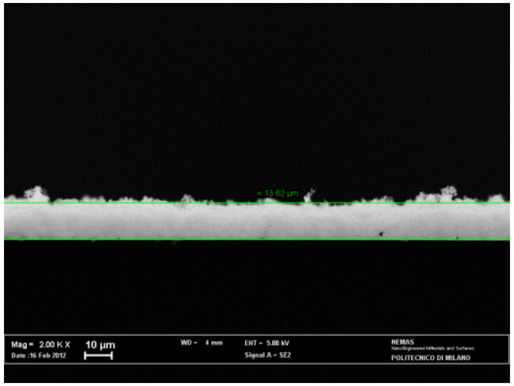


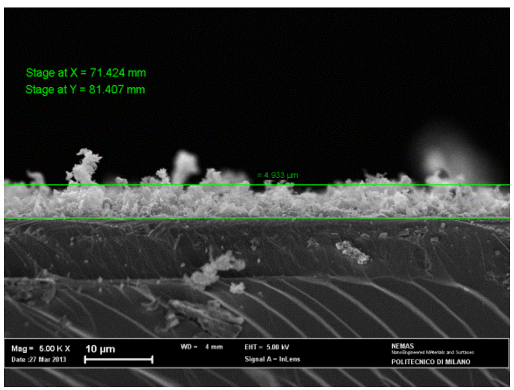
- Nearly pure sp^2 network of topologically disordered domains :
  odd-membered rings and few chain-like structures
- Ordered graphitic domains dimension ~ 2nm

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

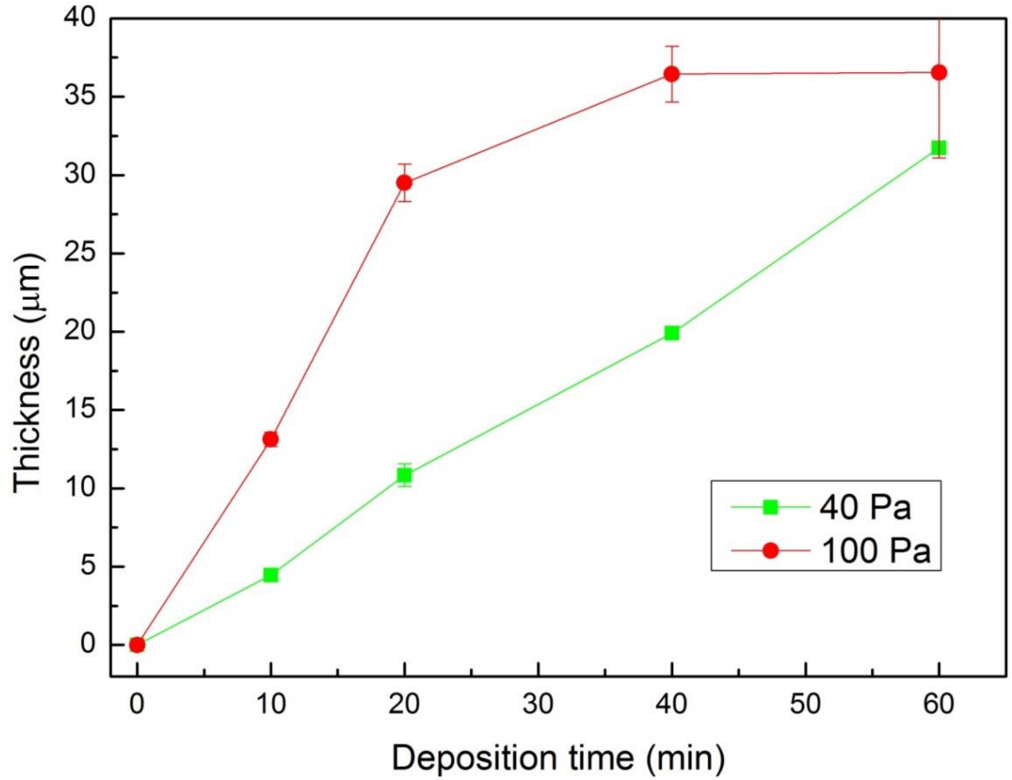
Thickness assessment

Cross-sectional SEM images





Thickness controlled through **deposition time** selection



Deposition in Argon

Low ambient gas pressure: linear trend

High ambient gas pressure: saturation – dynamic equilibrium

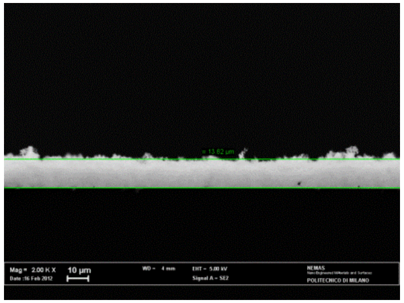
Density measurement

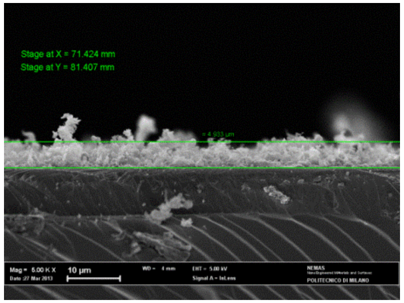
Thickness assessment

Areal density measurement

→ **DENSITY EVALUATION**

Thickness assessment: cross-sectional SEM images





Areal density measurement

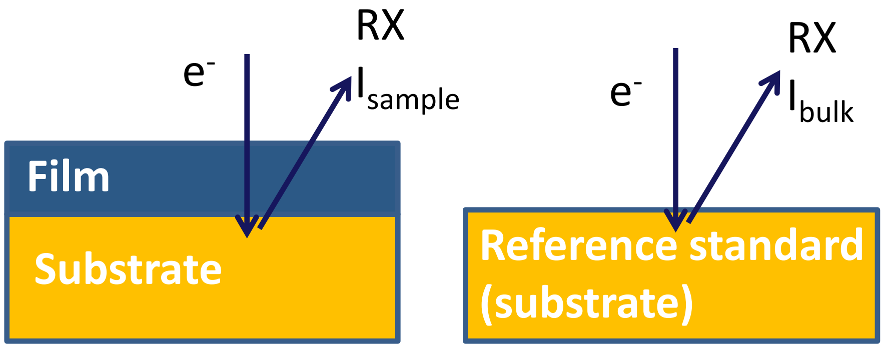
Conventional quartz-crystal microbalance (QCM) technique unreliable for densities under 20 mg/cm^3

new technique based on

Energy Dispersive X-Ray Spectroscopy (EDXS)

Areal density measurement

Energy Dispersive X-Ray Spectroscopy (EDXS)



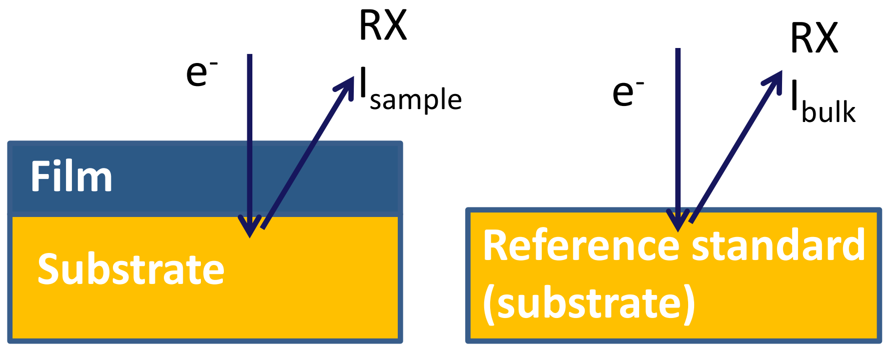
$$\frac{I_{sample}}{I_{bulk}} = \frac{\exp(-\chi_c t) \int_t^{\infty} \Phi^*_{Si}(\rho z) \exp[-\chi_s(\rho z - t)]\, \mathrm{d}(\rho z)}{\int_0^{\infty} \Phi_{Si}(\rho z) \exp(-\chi_s \rho z)\, \mathrm{d}(\rho z)}$$

- t film areal density → **UNKNOWN QUANTITY**
- $\frac{I_{sample}}{I_{bulk}}$ intensity ratio → **MEASURED QUANTITY**
- $\Phi_{Si}(\rho z)$ Probability Function for X-Ray Production (PFXP) → evaluated through a proper **MODEL**

H. E. Bishop et al. *Phys. D: Appl. Phys*, **6**, 1142 (1973)

Areal density measurement

Energy Dispersive X-Ray Spectroscopy (EDXS)



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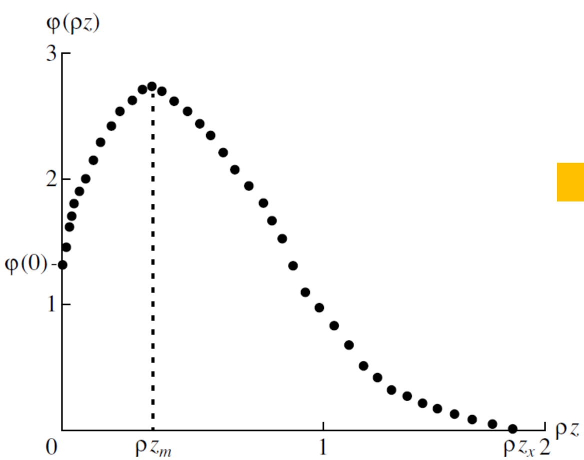


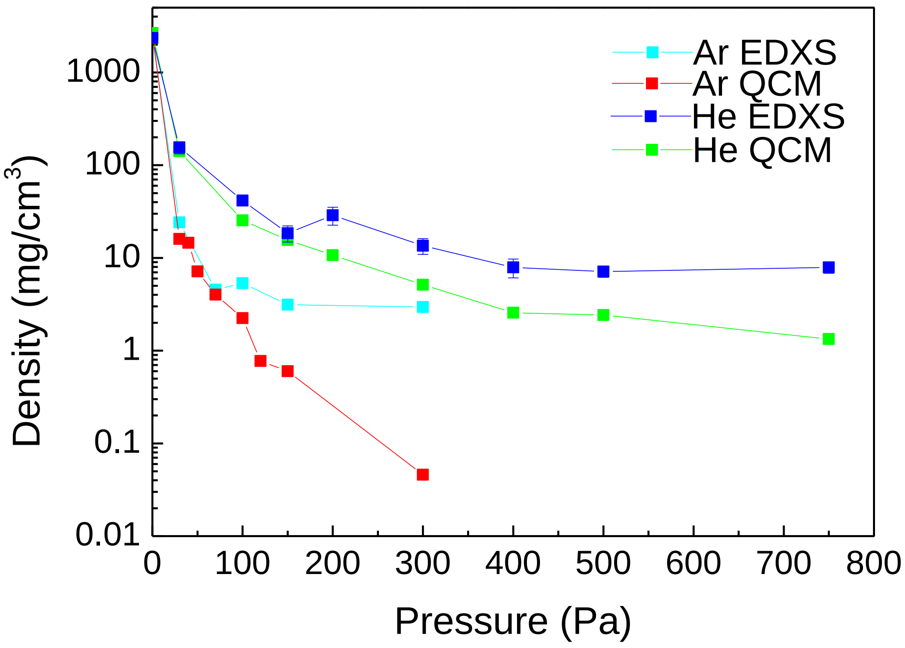
$\Phi_{Si}(\rho z)$ surface centered gaussian function

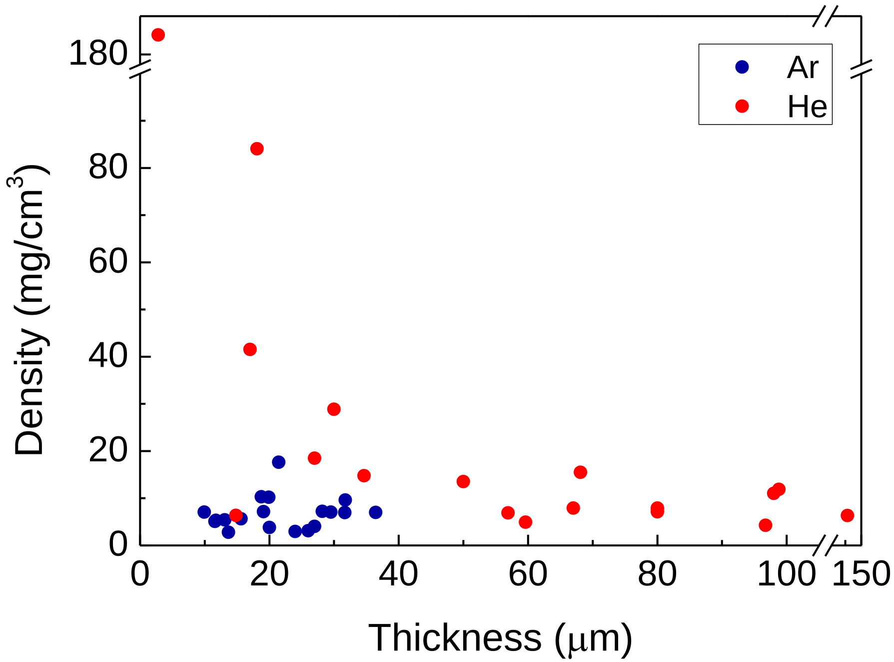
\+

surface correction

Yu. G. Lavrent'ev et al. *J. Anal. Chem*, **59**, 600 (2004)

Results





DENSITY

- down to 3 mg/cm^3
- controlled tuning GAS PRESSURE

THICKNESS

- from 10 μm to 150 μm
- controlled selecting DEPOSITION TIME

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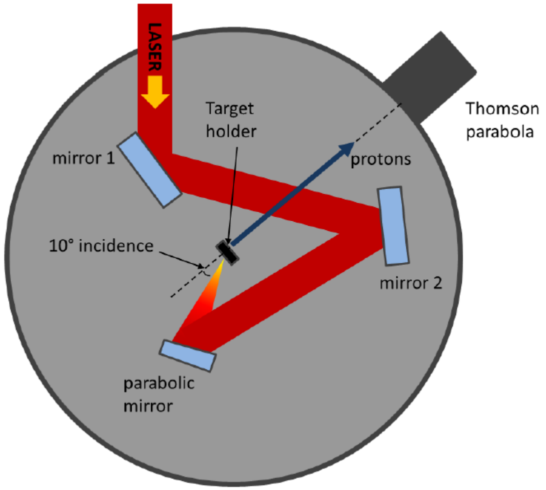
Acceleration experiments @ UHI100 CEA

Experimental setting



LASER PULSE

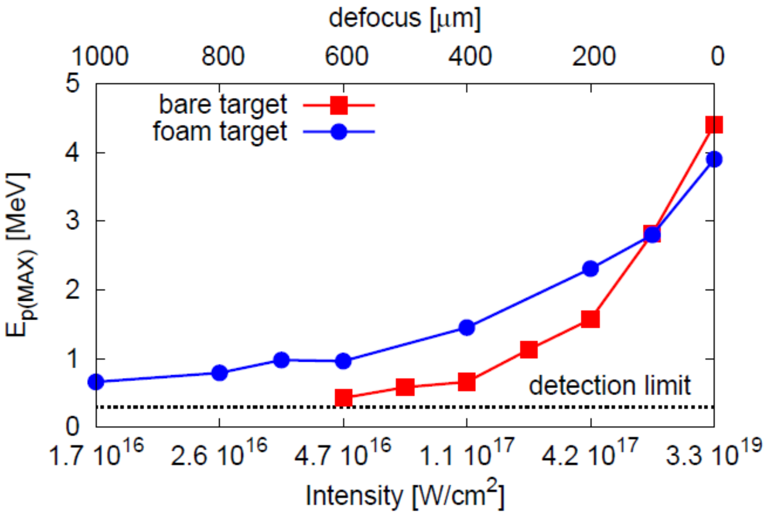
τ_L = 25 fs
E_L = 2 J
$I_L = 5\times10^{16} - 5\times10^{19}$ W/cm^2
w_0 = 3.5 - 150 µm
λ = 0.79 µm ➡ ρ_c=5.7 mg/cm^3
Low contrast 10^9 (LC)
High contrast 10^{12} (HC)

MULTI-LAYERED TARGETS

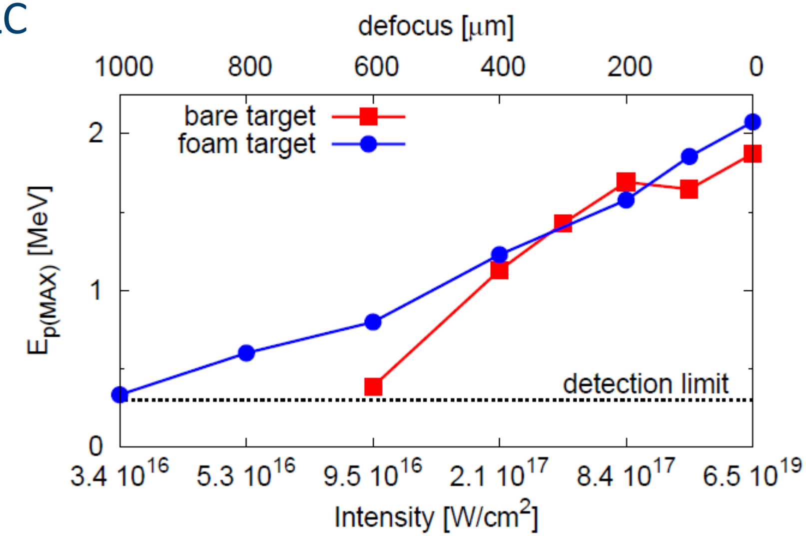
Al foil 1.5 µm (HC) – 10 µm (LC)
C foam 12 µm (HC) – 23 µm (LC)

Results: maximum energy of accelerated ions

HC

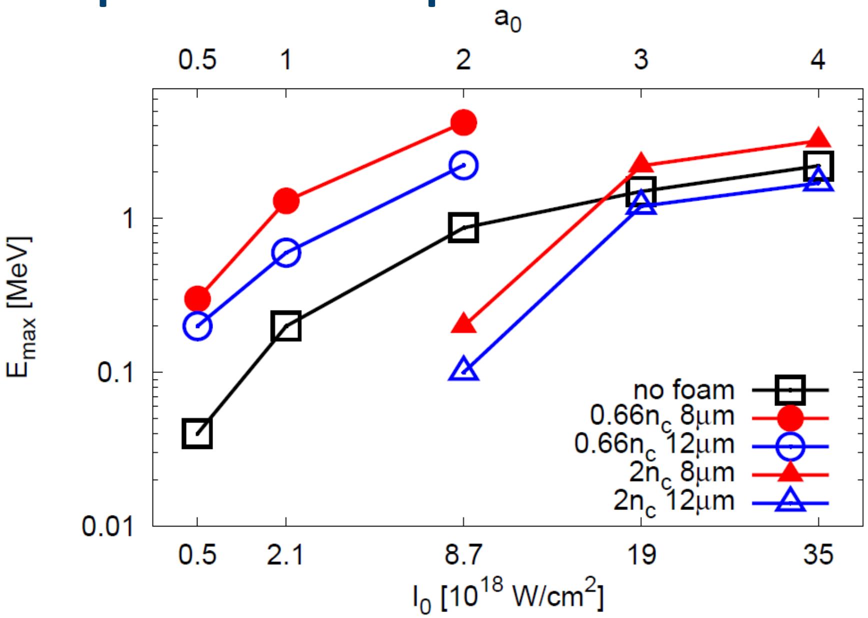


LC



Acceleration experiments @ UHI100 CEA

Interpretation of experimental results



2D PIC SIMULATIONS

τ = 25 fs

a = 2-4: focal spot 3-12 μm

a = 0.5-1: focal spot 12 μm

(see also A. Sgattoni's talk)

TWO INTERACTION REGIMES

$I > 10^{18}$ W/cm²

Complete foam ionization (C^{6+})

slightly over-critical plasma

TNSA-like scheme

comparable maximum proton energy

(bare vs multi-layered target)

$I < 10^{18}$ W/cm²

Partial foam ionization (C^{2+}/C^{4+})

sub-critical plasma (0.5 n_c)

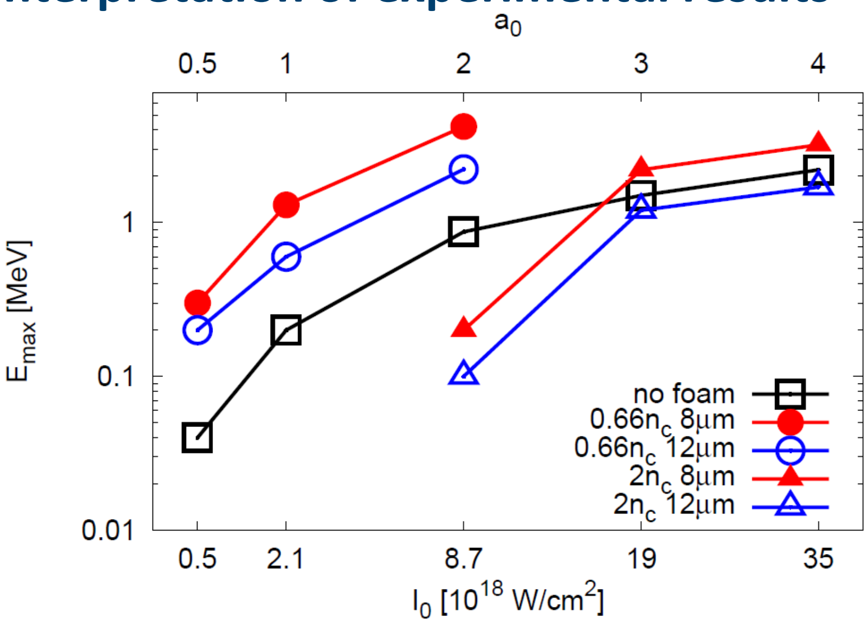
e^-_{hot} from volume interactions

higher proton energy

with foam-attached targets

Acceleration experiments @ UHI100 CEA

Interpretation of experimental results



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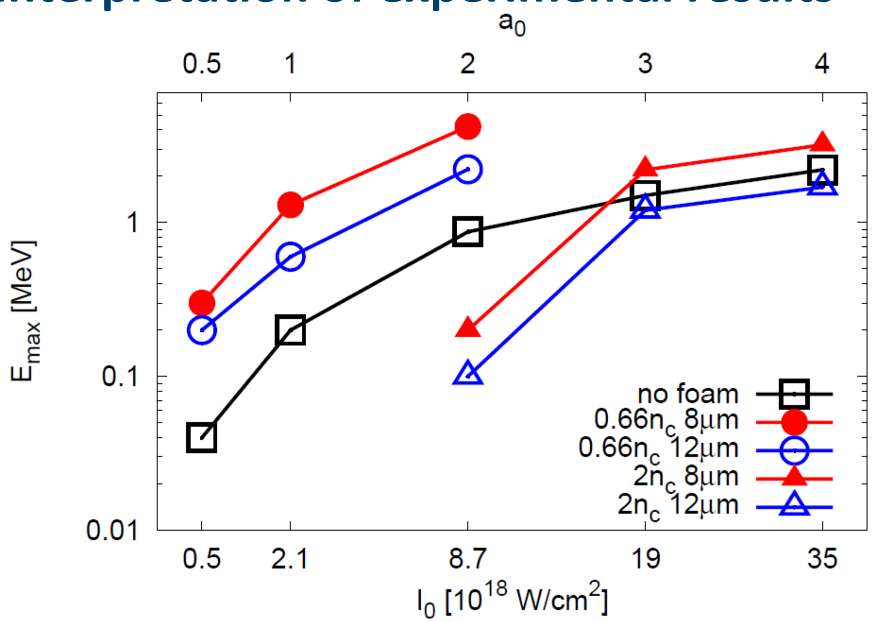
ENHANCED PROTON ACCELERATION REGIME

Acceleration experiments @ UHI100 CEA

Interpretation of experimental results



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TWO INTERACTION REGIMES

$I>10^{18}$ W/cm²

With suitable matching of the **target properties** with the **laser parameters**

PRODUCTION OF **10^2 MeV PROTONS** SHOULD BE ACHIEVED

$I<10^{18}$ W/cm²

Partial foam ionization (C^{2+}/C^{4+})

sub-critical plasma (0.5 n_c)

e^-_{hot} from volume interactions

ENHANCED PROTON ACCELERATION REGIME

Conclusions…

Production of carbon foams by PLD

- density controlled tuning gas pressure (down to 3 mg/cm^3)
- thickness controlled selecting deposition time (10 – 150 µm)
- random porous morphology
- good uniformity and adhesion on substrate

Characterization of low density carbon foams

- new method based on EDXS for areal density measurement

Test of multi-layered targets in acceleration experiments (TNSA scheme)

- enhanced maximum proton energy for moderate intensities (< 10^{18} W/cm^2)
- possibility to enhance maximum proton energy for high intensities with optimized target properties

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… and perspectives

- more satisfactory control of foams properties
- other materials (i.e. hydrogenated carbon foams)
- target testing in further acceleration experiments

Thank you

- Alessandro ZANI
- David DELLASEGA
- Valeria RUSSO
- Tiberio CECCOTTI
- Vincent FLOQUET
- Andrea SGATTONI
- Andrea MACCHI
- Matteo PASSONI

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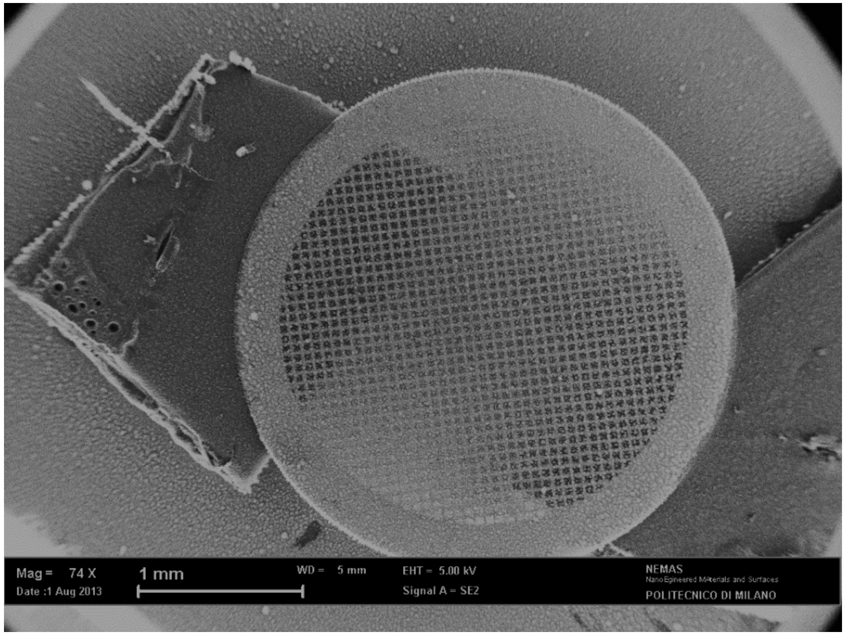
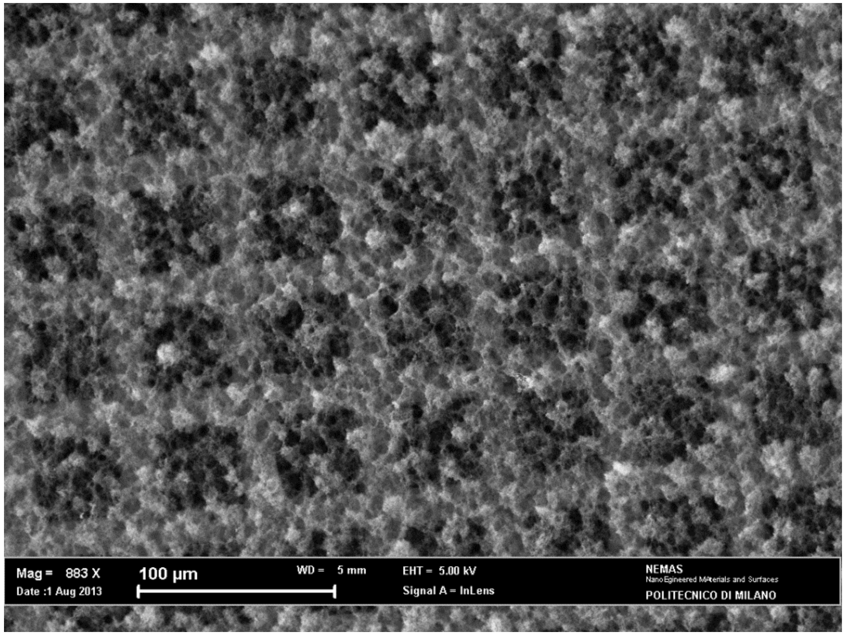
cea

IN SUPREMÆ DIGNITATIS 1343
UNIVERSITÀ DI PISA

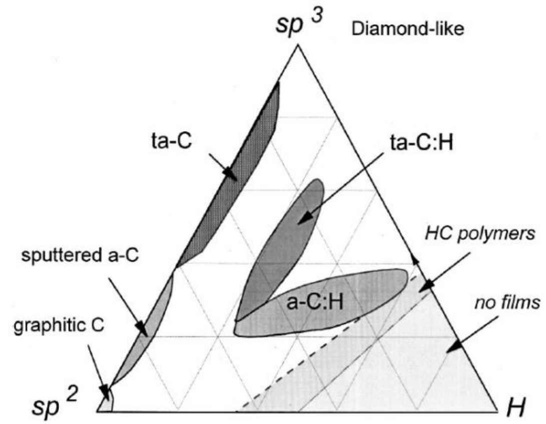
Carbon foams on TEM grids



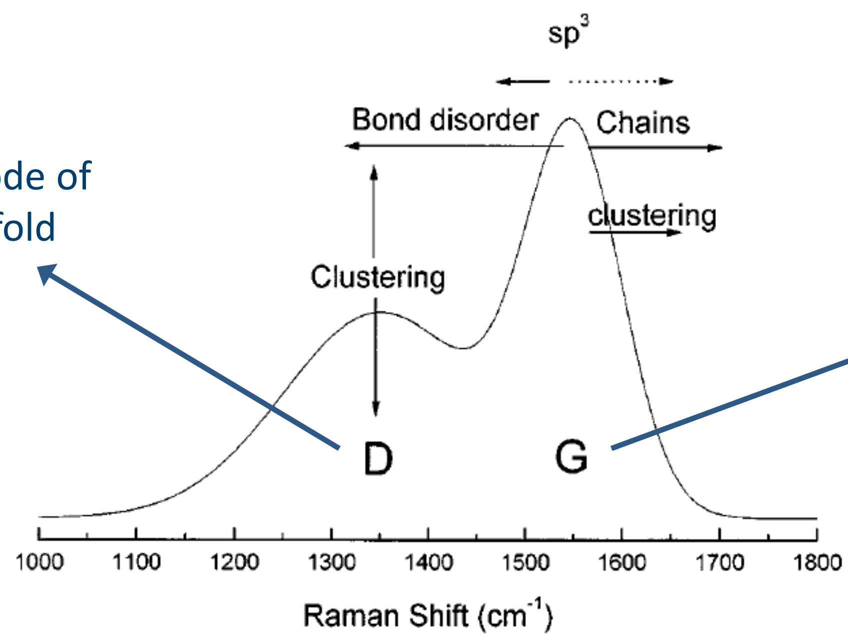


Raman spectroscopy of carbon films

- amorphous carbon (a-C): mixture of sp, sp^2, sp^3 phases
- Raman spectrum of a-C dominated by sp^2 features: G and D peaks
- Raman spectrum of a-C controlled by the order, not by the amount of sp^2 phase and only indirectly by sp^3 fraction



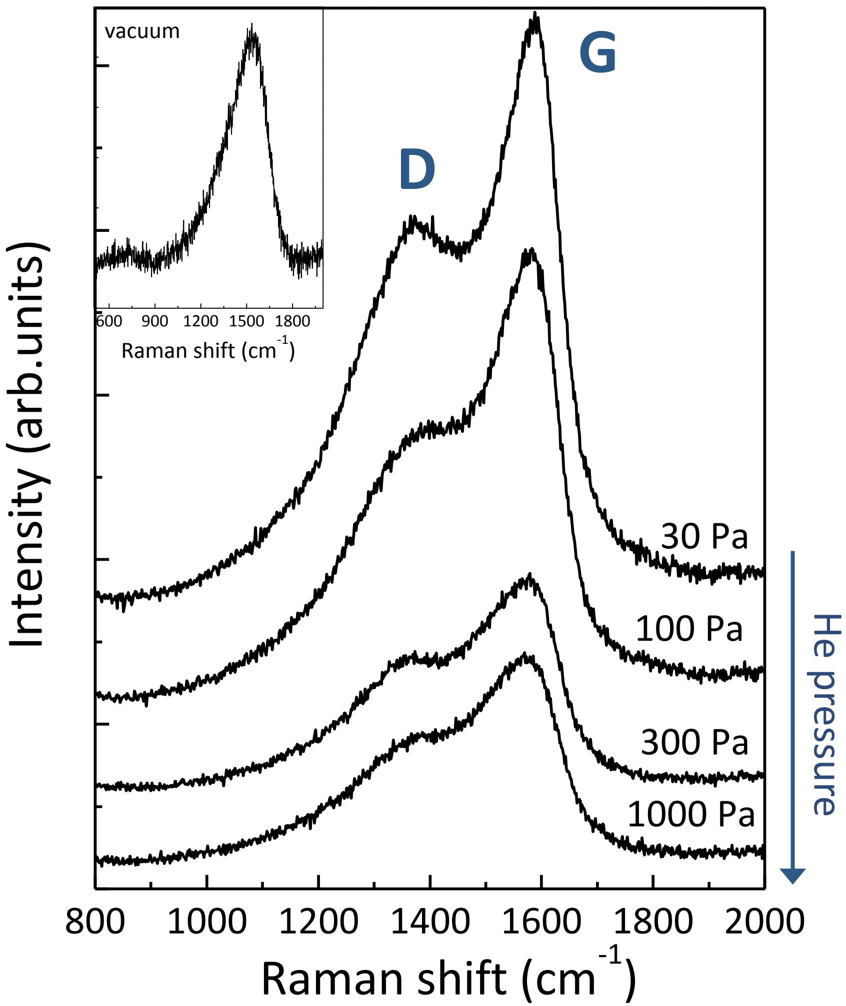
Breathing mode of aromatic six-fold rings



stretching mode of sp^2 C-C pair

Ferrari AC and Robertson J, Phys. Rev. B 61 (2000) 14095

PLD carbon foams: Raman spectroscopy



- Similar Raman spectra, typical of a-C, at any pressure, both for argon and helium
- Some differences in peak positions and relative intensities
- Fitting procedure
  - Asymmetric Breit-Wigner-Fano (BWF) function for G peak
  - Lorentzian function for D peak
    [Ferrari AC, Robertson J, Phys. Rev. B 61 (2000) 14095]

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

Raman spectra interpretation

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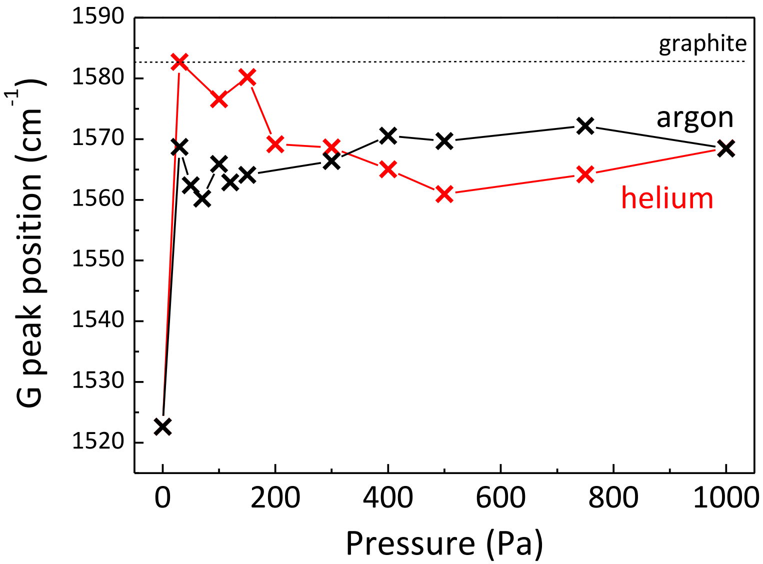
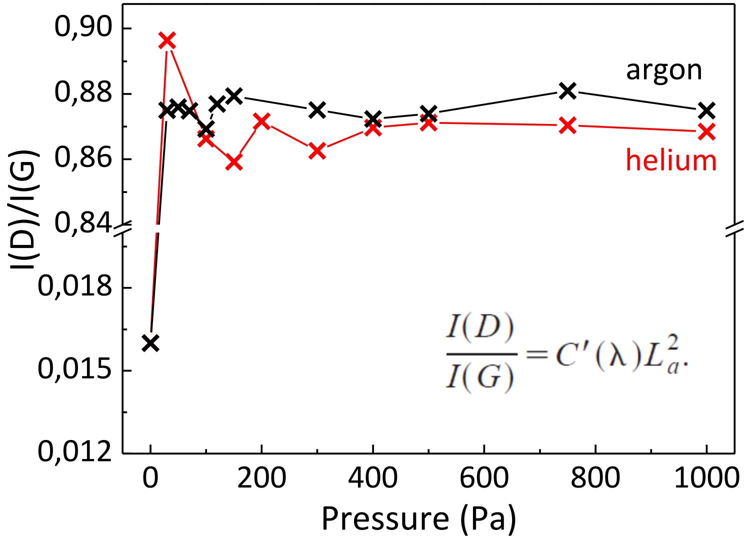
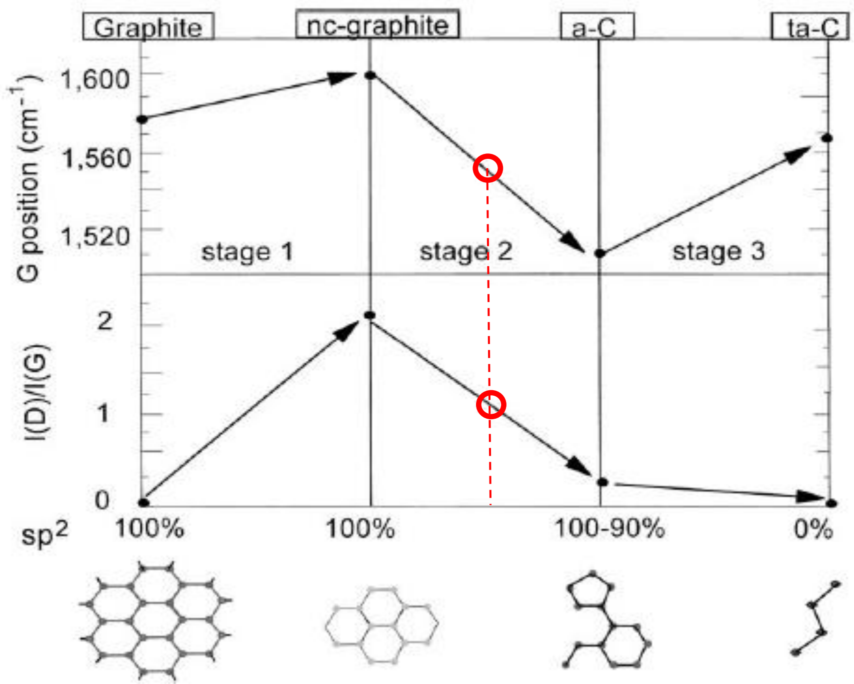




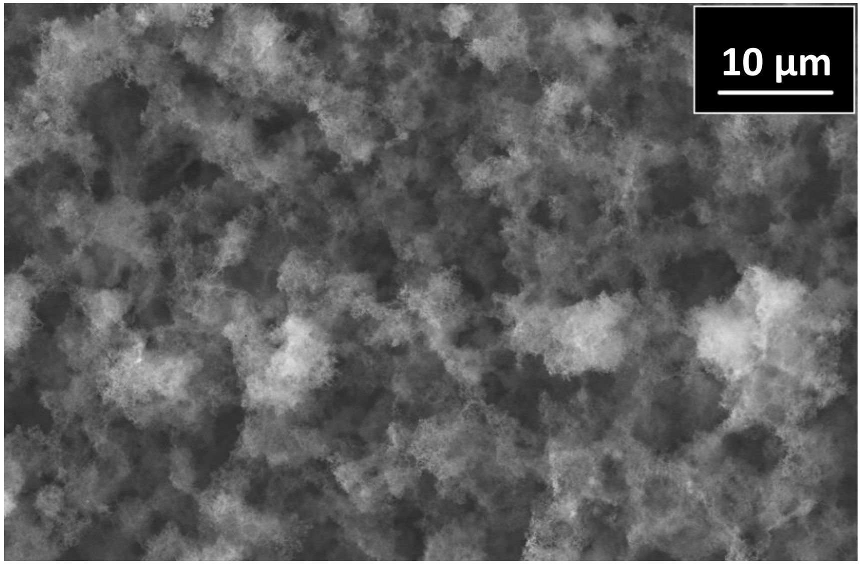


[Robertson J, Mat. Sci.&Eng R 37 (2002) 129]

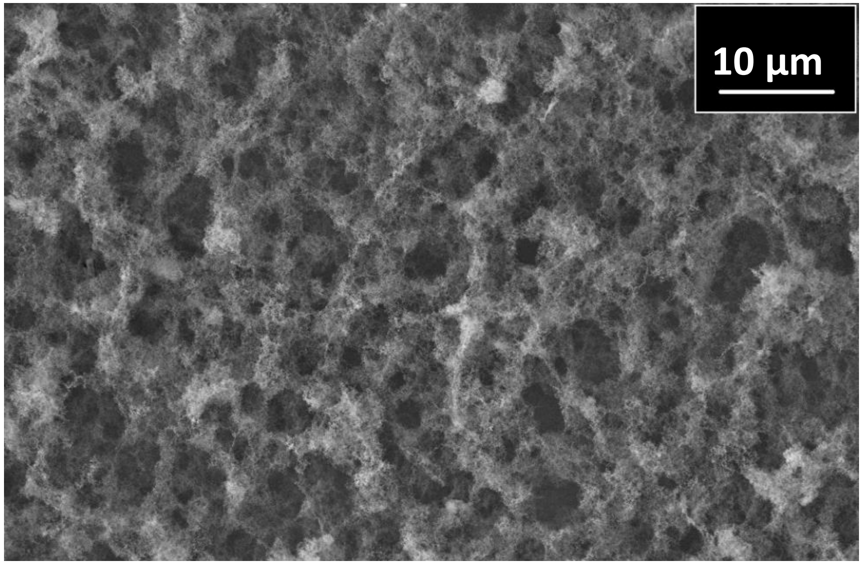
- Nearly pure sp^2 network of topologically disordered domains
- Some loss of aromaticity
- Odd-membered rings and few chain-like structures
- From I(D)/I(G) ~ 0,86 → L_a < 2nm (dimension of ordered graphitic domains)

Role of gas flux in the deposition chamber

SEM images



0.03 mg/s TRANSVERSE FLOW



9 mg/s DIRECTIONAL FLOW

The presence of a **directional flow** increases the **surface uniformity**