POLITECNICO DI MILANO

Nanostructured materials for nuclear fusion and laser-driven ion acceleration

Alessandro Maffini

Dipartimento di Energia, NanoLab, Politecnico di Milano, Italy

alessandro.maffini@polimi.it

Outline

1) NanoLab @ PoliMi

2) Metallic coatings for magnetic fusion

- W films for plasma facing components
- Rh mirrors for plasma diagnostics

3) Targets for laser driven ion acceleration

- Enhanced acceleration regime
- C foams for multi-layered targets
- Experimental and numerical results

Politecnico di Milano

The Micro and Nanostructured Materials Laboratory **(NanoLab)** belongs to the Department of Energy of **Politecnico di Milano**

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 programs, 18 PhD programmes

Nanolab @ PoliMi

Head of the lab: Carlo E. Bottani (Full Professor)

5 Associate professors:
M. Beghi, P.M. Ossi, A. Li Bassi, C. Casari, **M. Passoni** [1,2]

4 Post-Doc researchers:
V. Russo [2], **D. Dellasega** [1,2], **L. Fedeli** [2], **A. Maffini** [1,2]

6 PhD candidates:
A. Pezzoli [1], F. Tumino, **L. Cialfi** [2], **E. Besozzi** [1] ,
F. Inzoli [1], L. Mascaretti

+ about 7 undergraduate students/year

NanoLab approach: comprehend & control physics at the **nanoscale** to:

- Understand materials behavior in unconventional/extreme conditions
- New materials for advanced application (photovoltaics, nuclear power, …)

Relevant projects in the frame of the WG4:

EUROfusion

[1] EUROfusion consortium

First will materials and plasma facing components for **magnetic fusion**

[2] ERC grant "ENSURE"

Ultraintense **laser-matter interaction** for secondary **ion beam** production

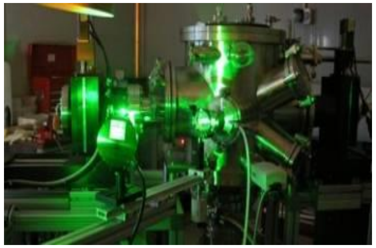
Nanolab @ PoliMi

Areas of expertise

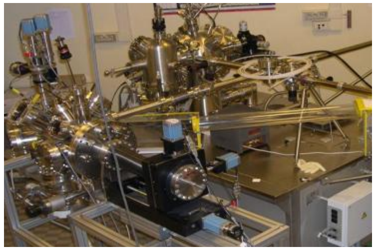
Analytical/numerical modelling of laser-plasma interaction

Theoretical solid state physics

Thin films deposition and processing



PLD Nd:YAG
λ=266 nm-1064 nm,
7 ns, 1.8 J

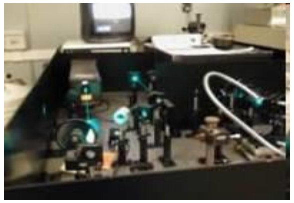


PLD KrF + STM
λ=248 nm, 12 ns,
450 mJ

+ Evaporator
+ Furnaces for thermal treatments

Material characterization

SEM + EDX:
Samples morphology,
Elemental Composition



Raman Spectroscopy:
Structural properties
Chemical composotion

+ STM/STS (surface analysis)
+ AFM (roughness)
+ Brillouin spectroscopy (vibrational)

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- C foams for multi-layered targets
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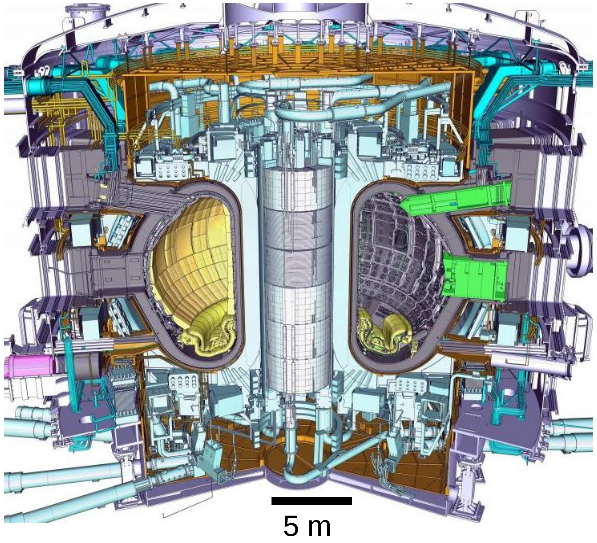
Magnetic confinement fusion

Milestone experiment: **ITER** (2022 ?)



- Started in 2013 in Cadarache (France)
- >18 billion € budget

- D-T fuel, 500 MW th.
- T ~ 10^8 K
- n ~ 10^{14} nuclei/cm^3
- τ_E ~ seconds

➢ **Radiation** fields (~ 2×10^3 Gy/s)
14 MeV neutrons + γ and x-rays

➢ **Particle bombardment** (~ 10^{18} m^{-2} s^{-1})
α, energetic neutrals + T

➢ Intense **thermal loads** (~ 500 MW/m^2)

Magnetic confinement fusion

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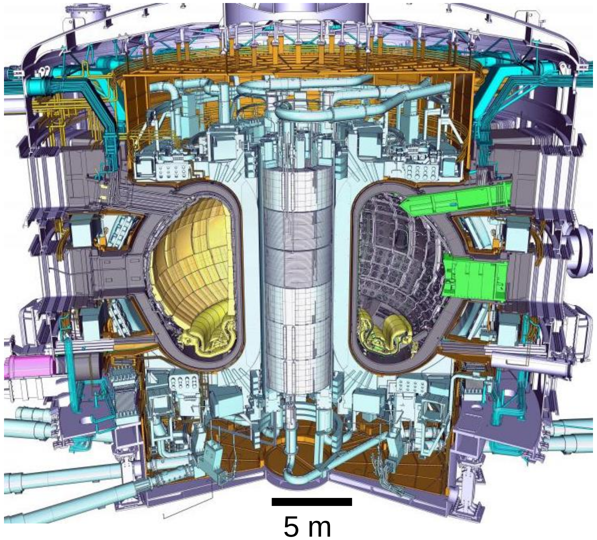

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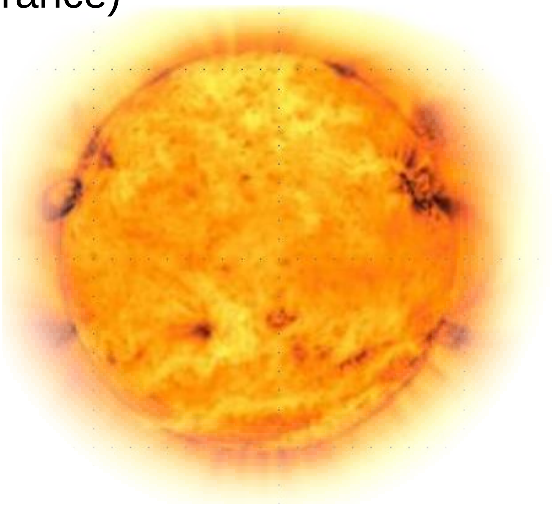

*"We say that we will **put the sun into a box**. The idea is pretty…..*
*…..The problem is, we don't know **how to make the box**".*

Pierre-Gilles de Gennes (1991 Nobel laureate in Physics)

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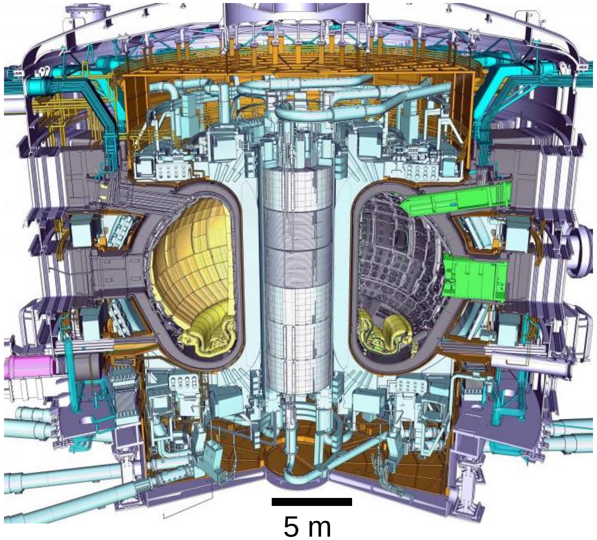

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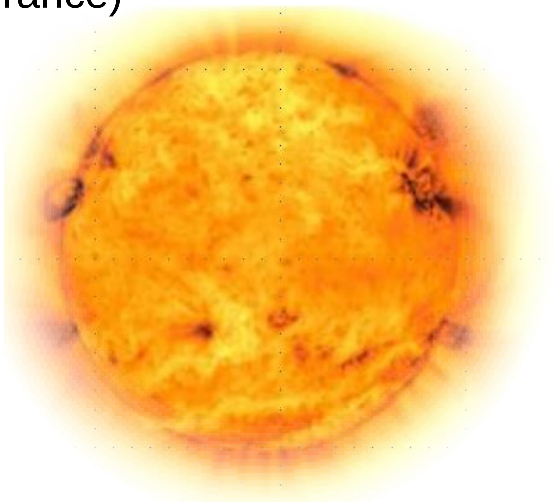

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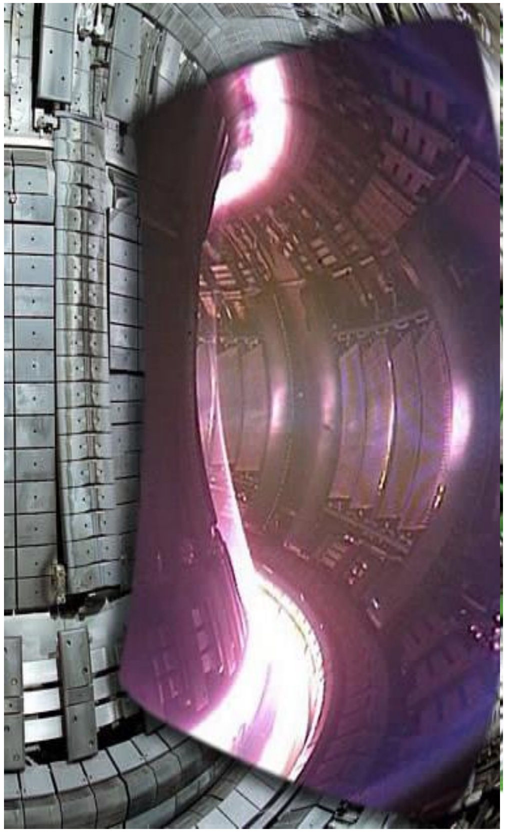
Tremendous challenge: First wall materials

First Wall in magnetic confinement machines

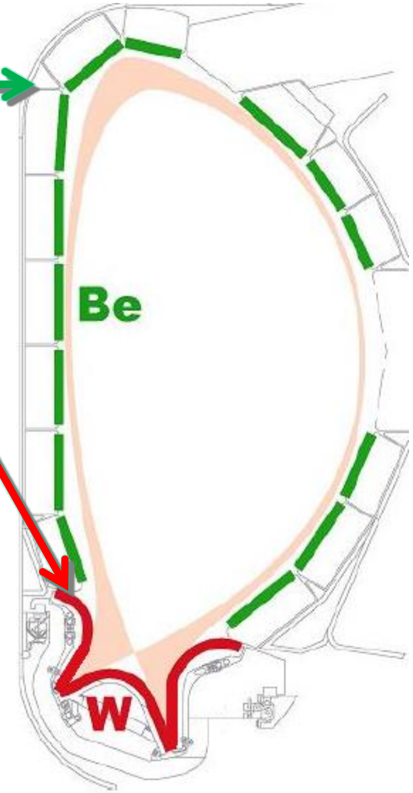
JET tokamak (Culham, UK)



Plasma Facing Components (PFC)

- First wall of the vacuum vessel
- Divertor (heat and particle sink)
- Many vital auxiliary systems (Heating, Diagnostics, …)

ITER first-wall



Issues:

Plasma particles **Radiation**

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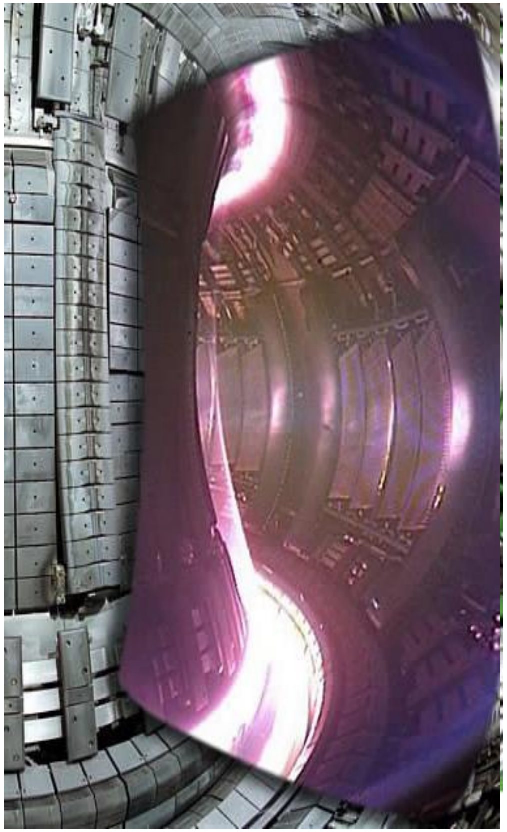

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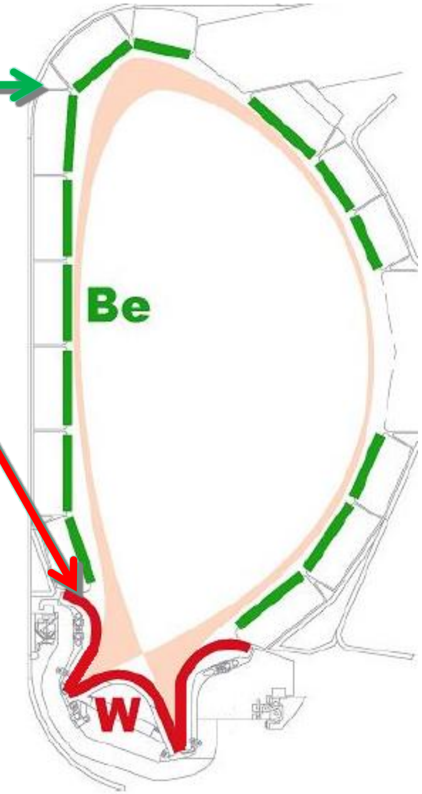

Issues:

Plasma particles → **Radiation** →

Material modification

→ **Erosion** → **Component failure**

→ **Performance decrease**

First Wall in magnetic confinement machines

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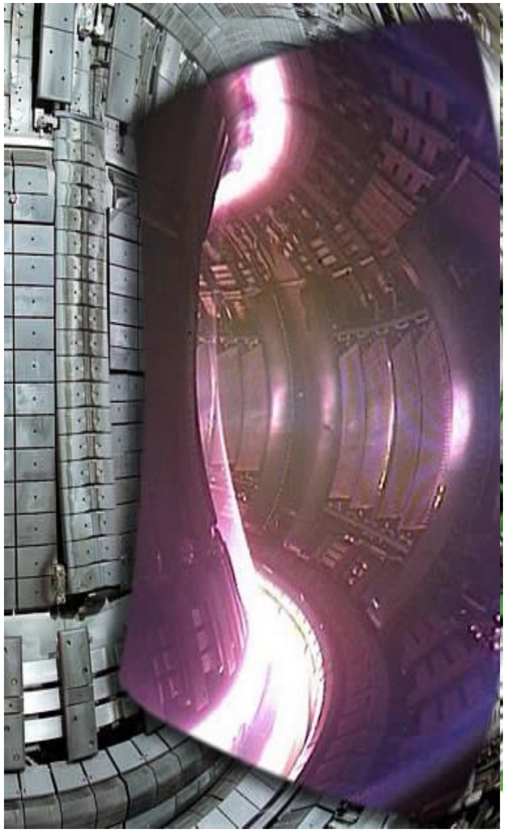

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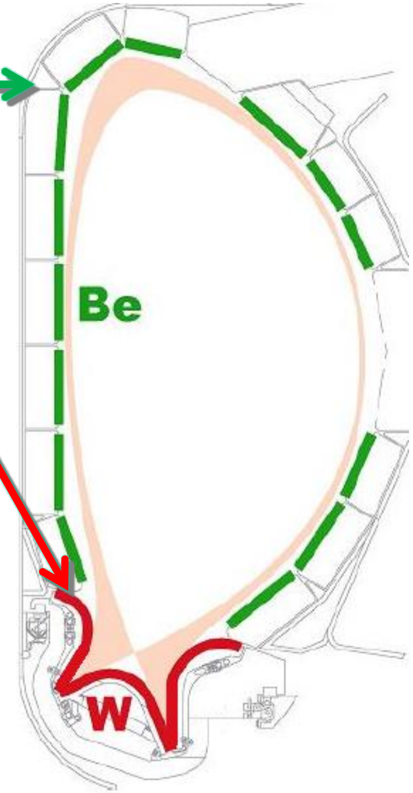

Issues:

Plasma particles → Material modification ← **Radiation**

Material modification → **Erosion**

Material modification → **Performance decrease**

Erosion → **Component failure**

Erosion → Plasma pollution

Plasma pollution → **Performance decrease**

Plasma pollution → **Contaminant re-deposition**

Contaminant re-deposition → **Component failure**

First Wall in magnetic confinement machines

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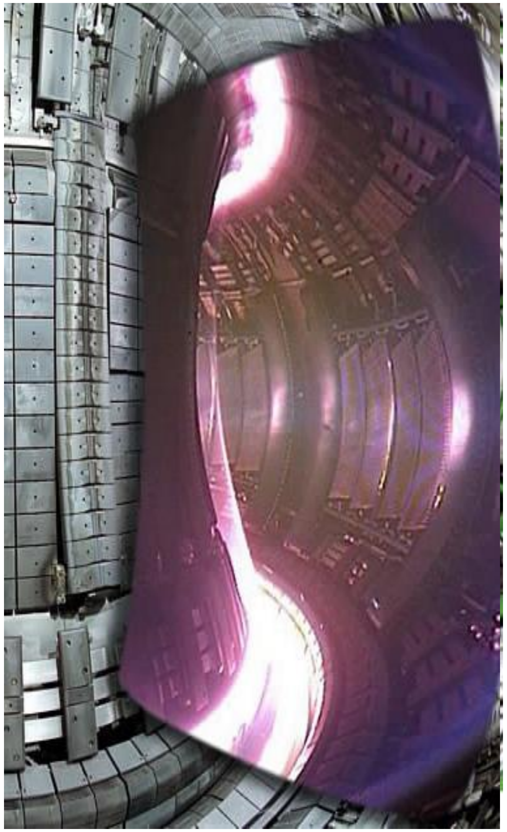

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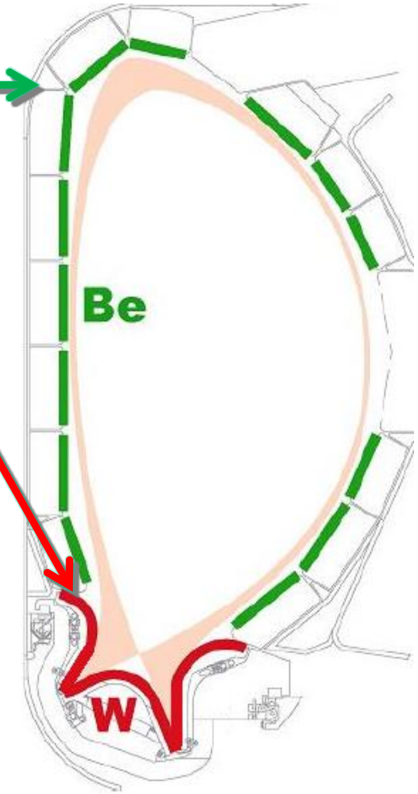

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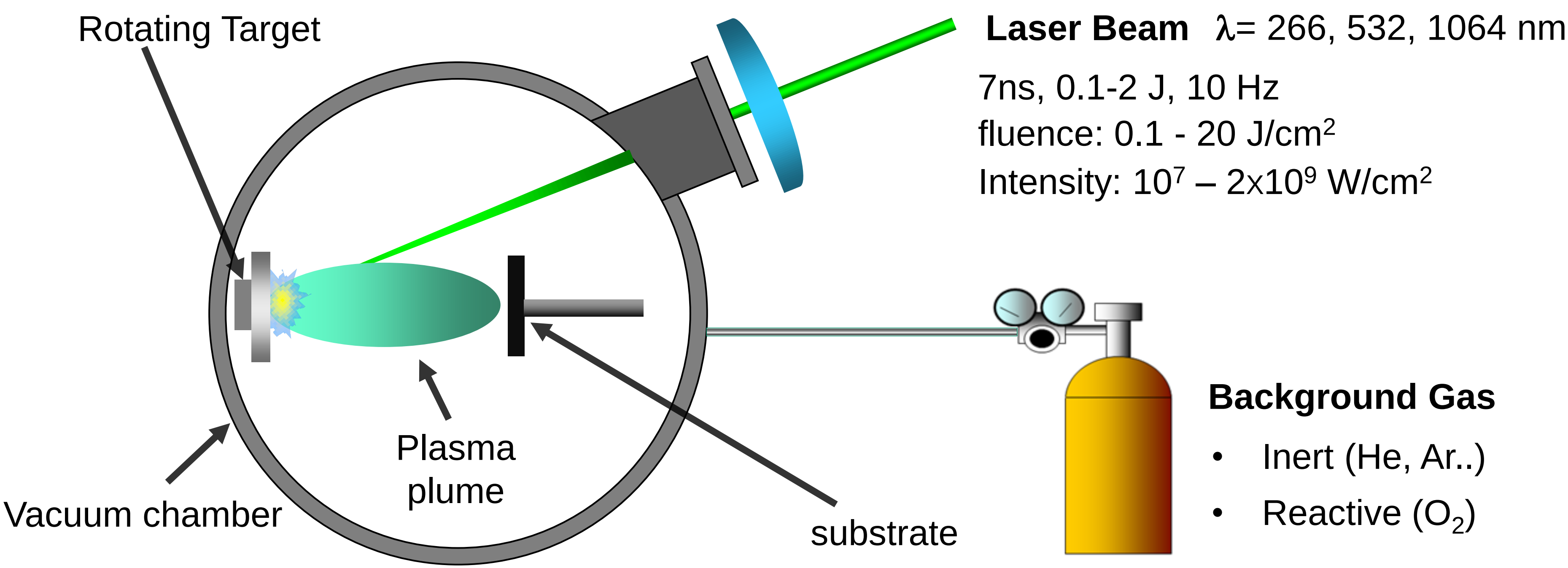
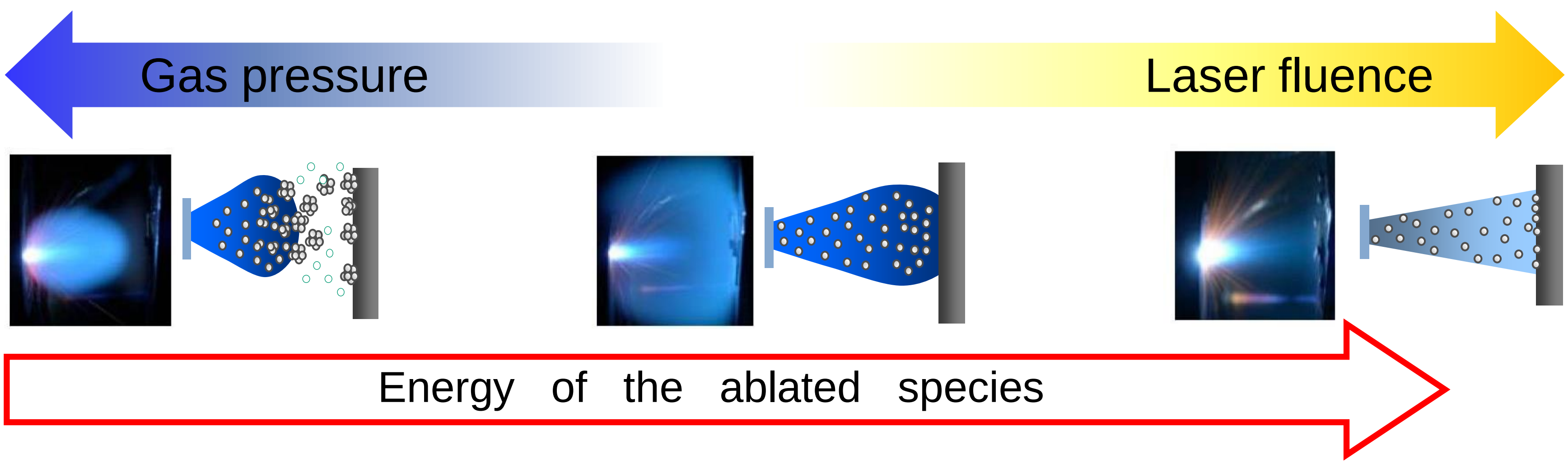
PLD @ NanoLab

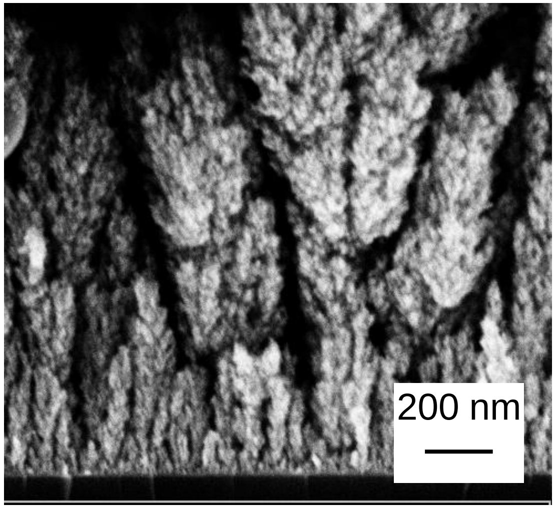
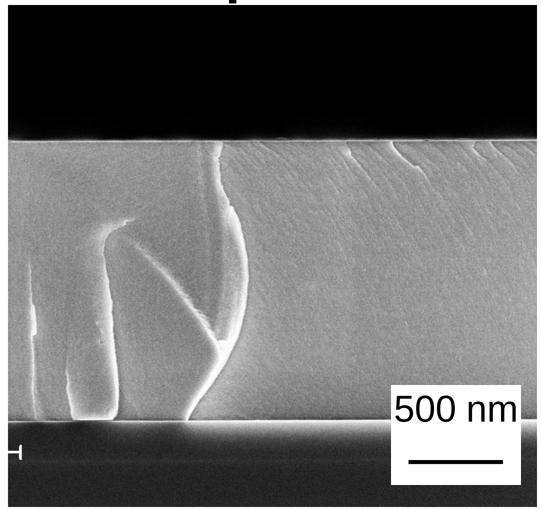
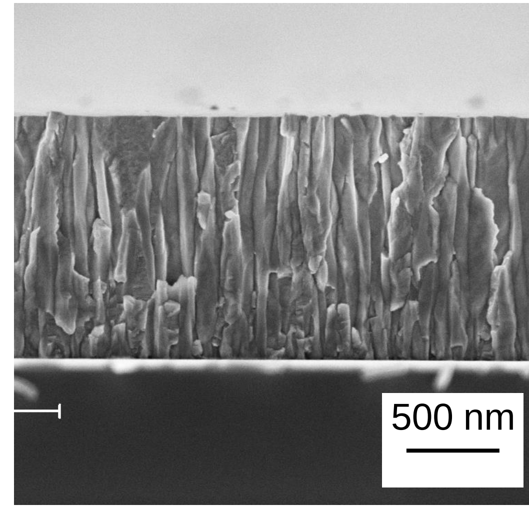
- **Nano-engineered components**
- **Lab-proxy of ITER materials**

Pulsed Laser Deposition





W coating for tokamak first Wall

W nanotrees	amorphous W	columnar W
		

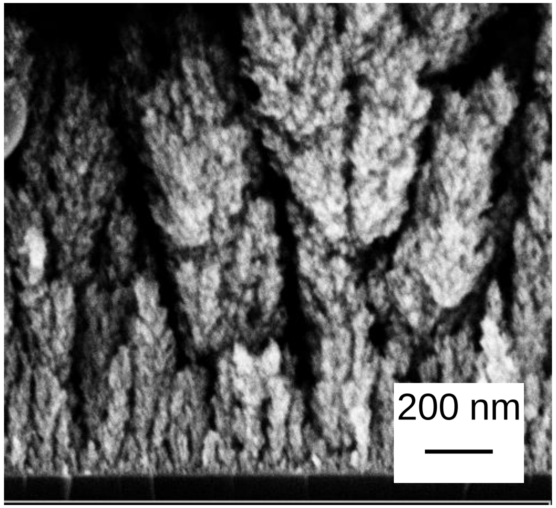
Energy of the ablated species

Porous morphology Crystallite dim. 15 nm	Compact morphology Crystallite dim. < 2 nm	Compact morphology Crystallite dim. 15 nm
Proxy of: **Redeposited/dust W**	Proxy of: **Redeposited/damaged W**	Proxy of: **W coating in JET**

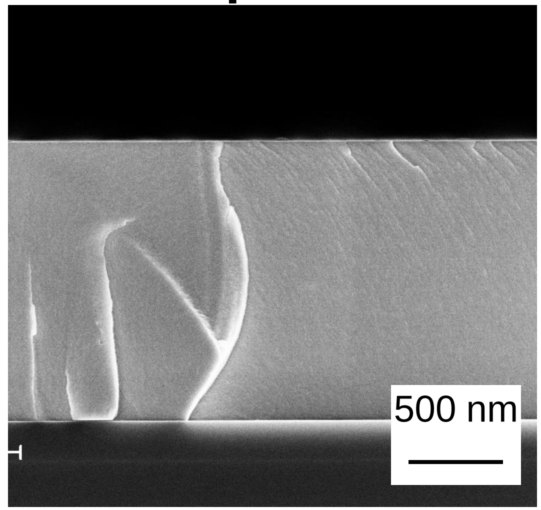
[1] D. Dellasega *et al.*, JAP 112 (2012) 084328

W coating for tokamak first Wall

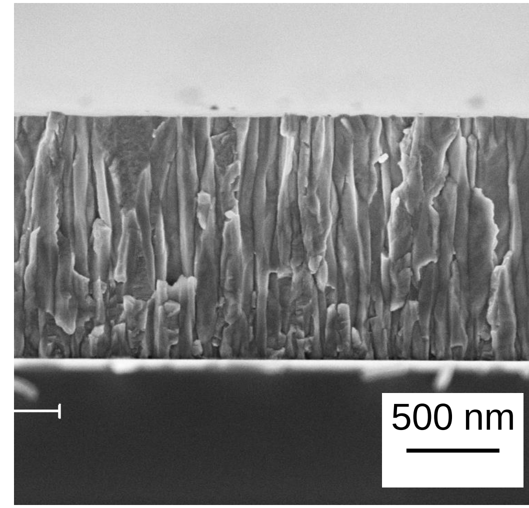
W nanotrees



amorphous W



columnar W



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Porous morphology
Crystallite dim. 15 nm

Proxy of:
Redeposited/dust W

Compact morphology
Crystallite dim. < 2 nm

Proxy of:
Redeposited/damaged W

Compact morphology
Crystallite dim. 15 nm

Proxy of:
W coating in ITER

+ T retention controlled by coating nanostructure!

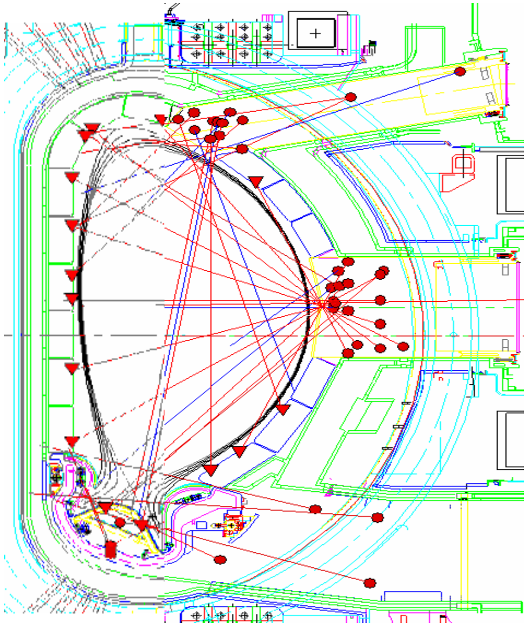
[1] D. Dellasega *et al*., JAP 112 (2012) 084328
[2] M.H.J. ‘t Hoen, et al., JNM, 463, 989–992, (2015)
[3] A. Pezzoli, et al., JNM, 463, 1041–1044, (2015)

Diagnostic first mirrors

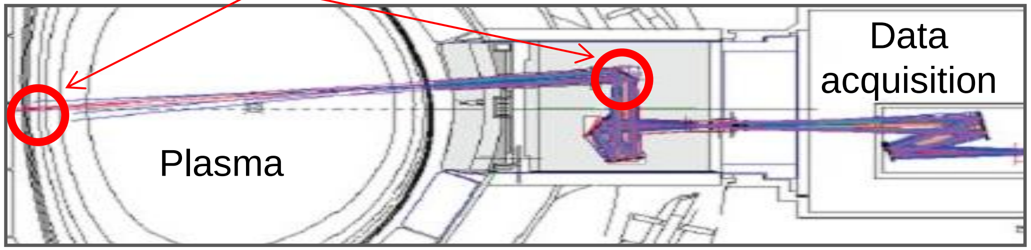
Optical diagnostics: analyse the light emitted from the plasma

- Essential for reactor operation & safety
- Data acquisition MUST be beyond radiological shield

→ Optical chain to extract the light



First Mirrors (FMs) : first ring of the optical chain



FMs are **critical components** working in an **extreme environment:**

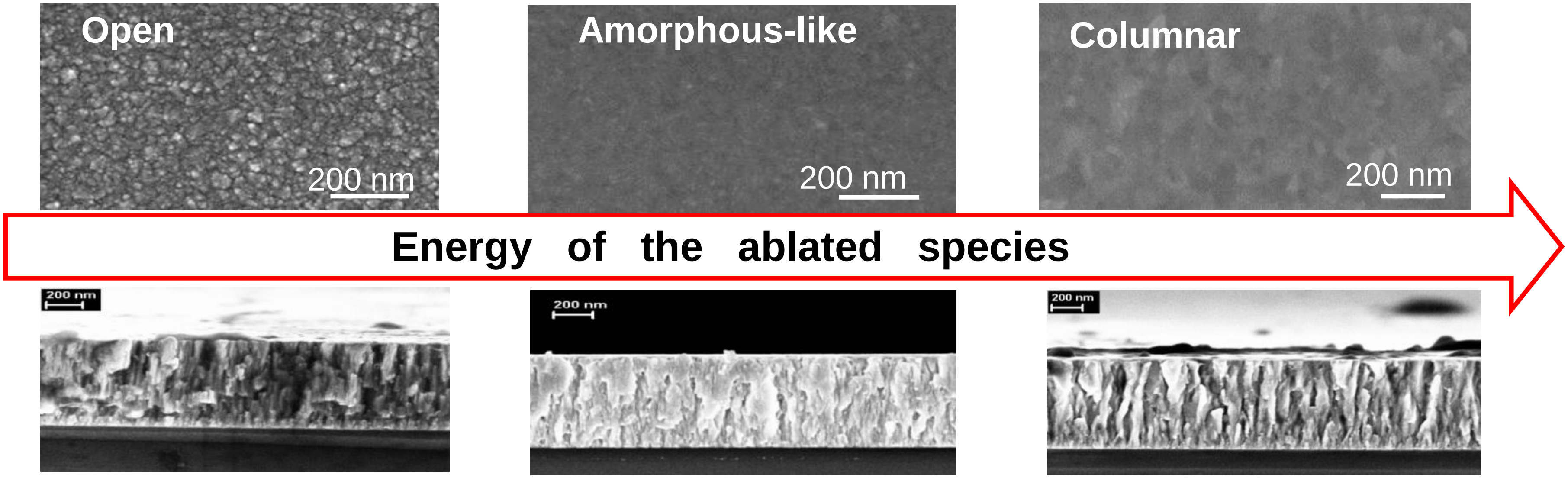
Vital: **Reflectivity** shall **not decrease**

Unavoidable **Plasma-FM interactions!**

Strict FMs **requirements**:

- Few candidate materials (SS, Cu, Mo, **Rh**)
- Different configurations (Single/Poly-crystal, **coating**)

Rh mirrors for optical plasma diagnostics



[A. Uccello, et al., *JNM.* **432** (2013) 261]

Rh mirrors for optical plasma diagnostics

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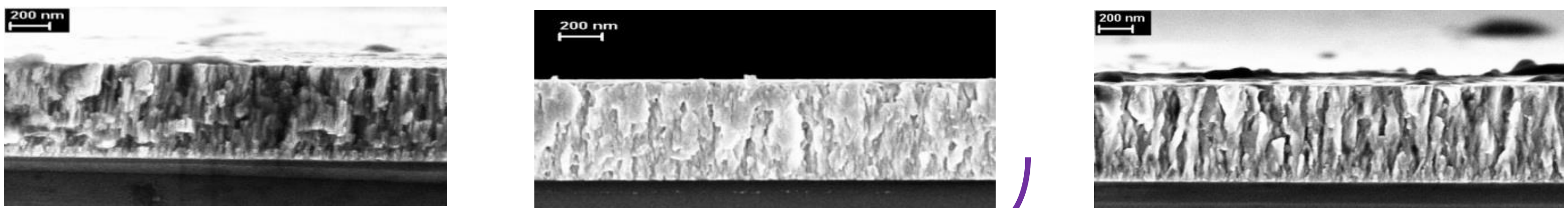
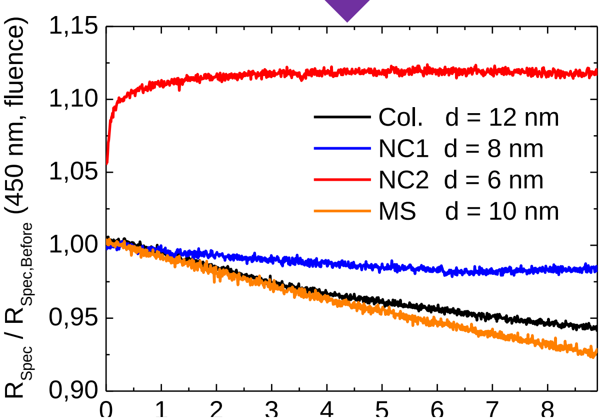


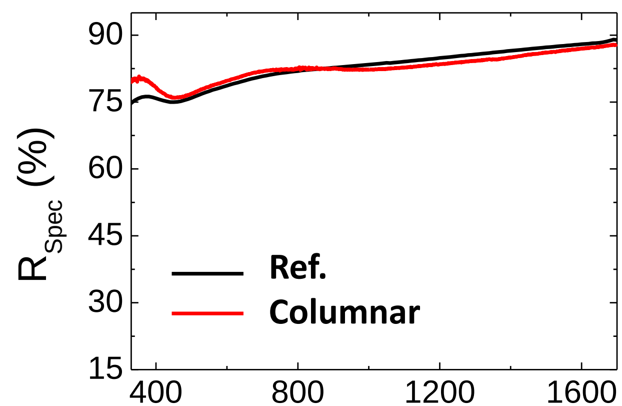
Better behavior under plasma erosion



[A. Uccello, et al., *JNM.* **446** (2014) 106]

Higher adhesion

Higher specular reflectivity



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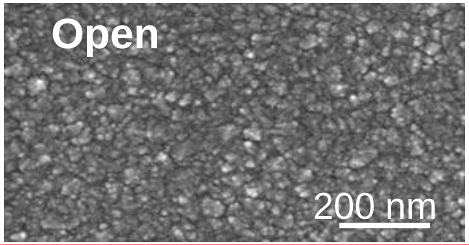

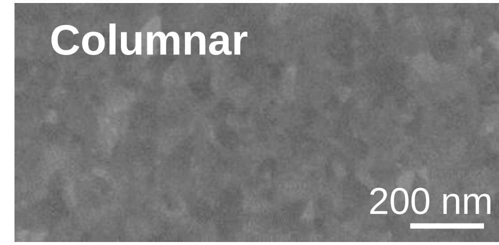

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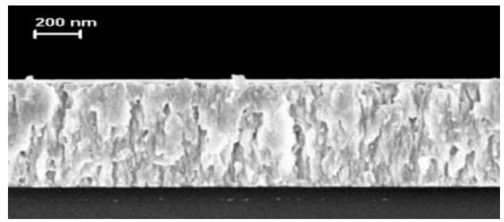

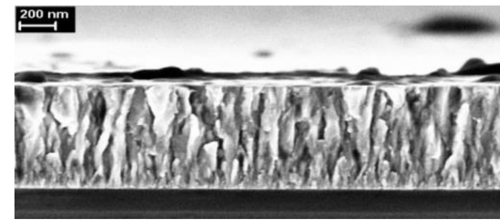

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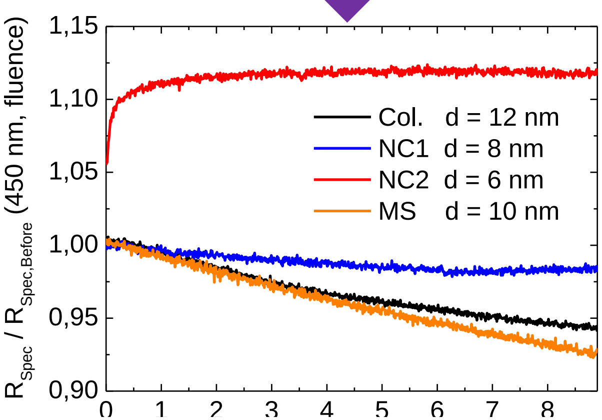
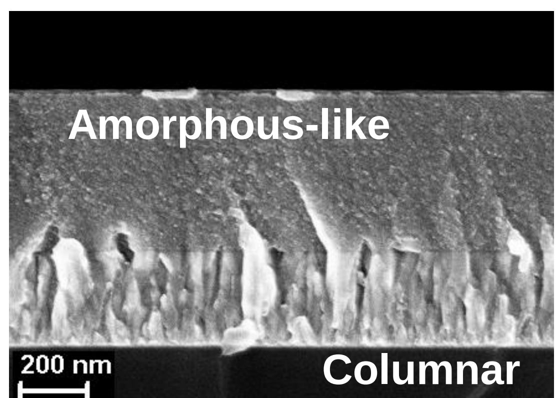
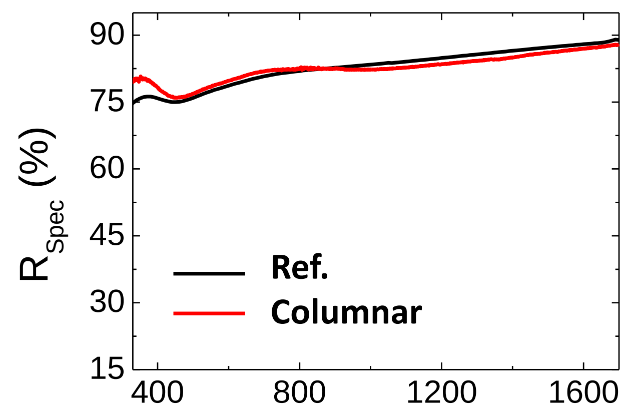


[A. Uccello, et al., *JNM.* **446** (2014) 106]

Multilayer solution!





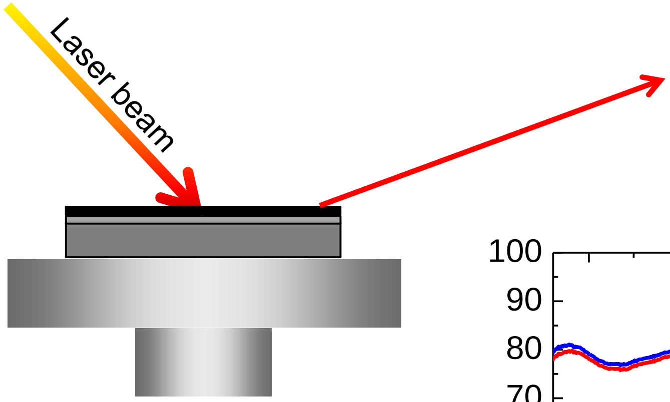
[A. Uccello, et al., *JNM.* **432** (2013) 261]

Laser cleaning of diagnostic mirrors

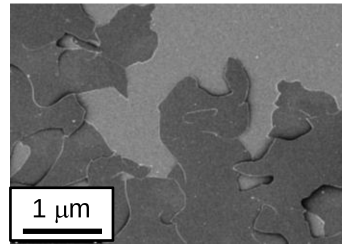
A. Maffini, et al. J. Nucl. Mater. 463 (2015) 944–947
A. Maffini, et al. Nucl. Fusion (2016) sumbitted

Laser pulses parameters

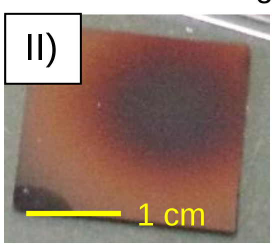
- λ=1064 nm 400 mJ/cm^2
- 45 pulse per site

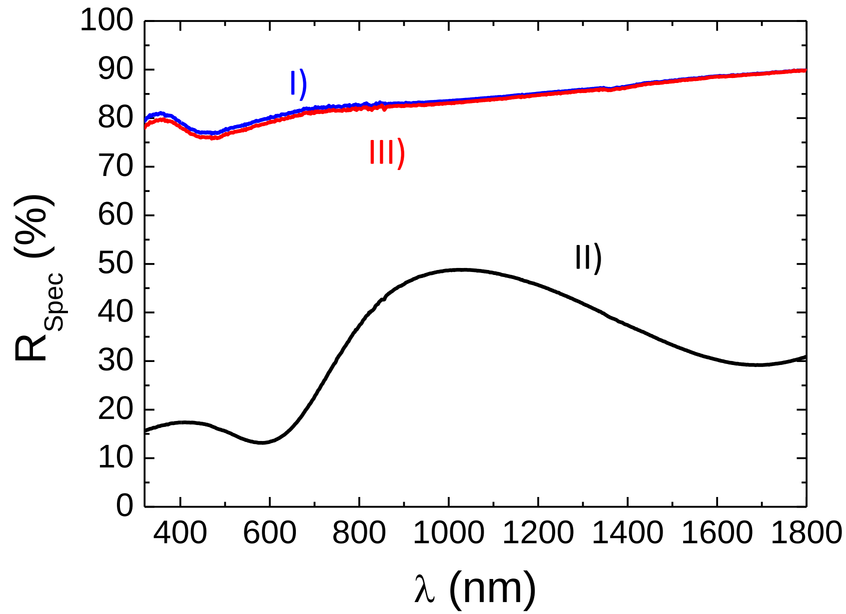


C compact film

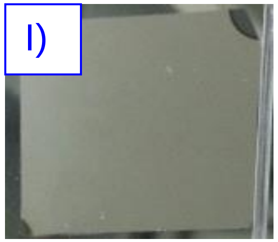


C/Rh before cleaning

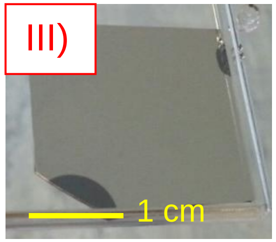




Rh film as deposited



C/Rh, IR cleaning



- Excellent R_{Spec} recovery!
- Different recipe for different materials
- Ok also for repeated cycles!

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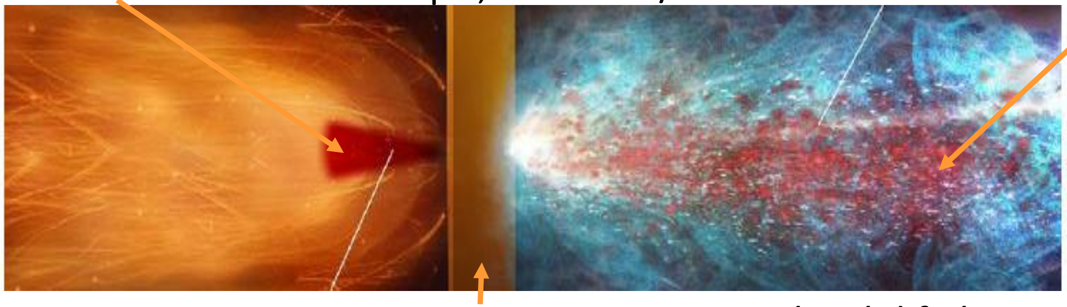
Laser driven ion acceleration

LASER PULSE: 10 fs -1 ps , I> 10^{18} W/cm^2



TARGET Conventional: solid foil
Novel: nanomaterial, gas jet, …

ACCELERATED IONS

- $E_{max} \approx 60$ MeV (H^+)
- ps ion bunches, good collimation
- 10^{11}-10^{12} ions/bunch
- Different mechanism proposed (TNSA, RPA, Collisionless Shock…)

LASER DRIVEN ION BEAMS:

- Proton imaging/radiography
- Warm dense matter
- Isotope production
- Cancer hadrontherapy
- **<u>Fast ignition in ICF</u>**

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

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GOALS:

- Increase E_{max} (up to 100 MeV/u)
- Increase ion number
- High rep. rate, high brillance

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

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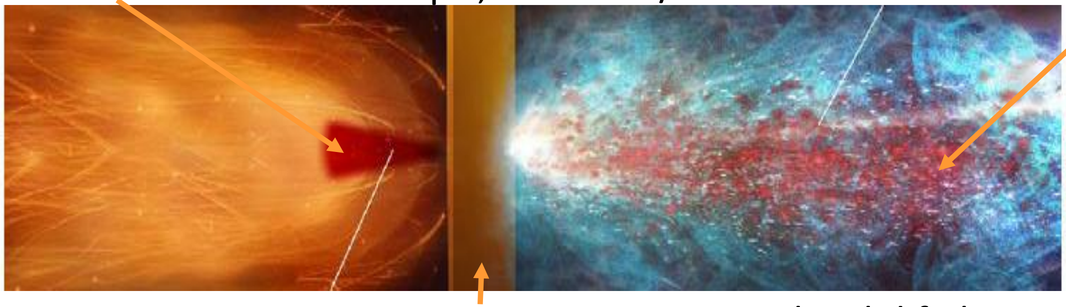
- Increase E_{max} (up to 100 MeV/u)
- Increase ion number
- High rep. rate, high brillance

STRATEGIES:
- Deeper theoretical comprehension
- Progress in laser technology
- **Novel target concepts!**

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

Laser driven ion acceleration

LASER PULSE: 10 fs -1 ps , I> 10^{18} W/cm^2



TARGET Conventional: solid foil
Novel: nanomaterial, gas jet, …

ACCELERATED IONS

- E_{max} ≈ 60 MeV (H^+)
- ps ion bunches, good collimation
- 10^{11}-10^{12} ions/bunch
- Different mechanism proposed (TNSA, RPA, Collisionless Shock…)

LASER DRIVEN ION BEAMS:

- Proton imaging/radiography
- Warm dense matter
- Isotope production
- Cancer hadrontherapy
- **Fast ignition in ICF**

GOALS:

- Increase E_{max} (up to 100 MeV/u)
- Increase ion number
- High rep. rate, high brillance

STRATEGIES:

- Deeper theoretical comprehension
- Progress in laser technology
- **Novel target concepts!**

PLD @ NanoLab

➢ **Nanofoam attached targets**

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

Goals and strategy of ENSURE project

Theoretical

Analytical descriptions, to gain insight into the relevant physics of the systems.

Particle-In-Cell (PIC) **numerical codes** to deal with multiscale physics & simulate "realistic" experiments

Experimental

Production of novel nanostructured material to enhance laser acceleration (e.g. nanofoam)

Characterization & understanding of novel/unconventional material features

Development of advanced micro- and nano-engineered targets

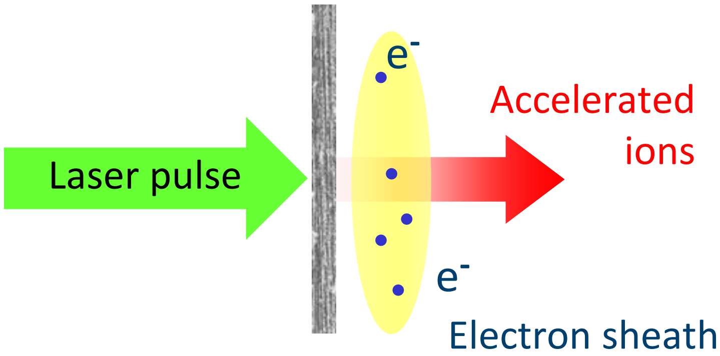
Laser driven ion acceleration experiments

In collaboration with external laser facilities

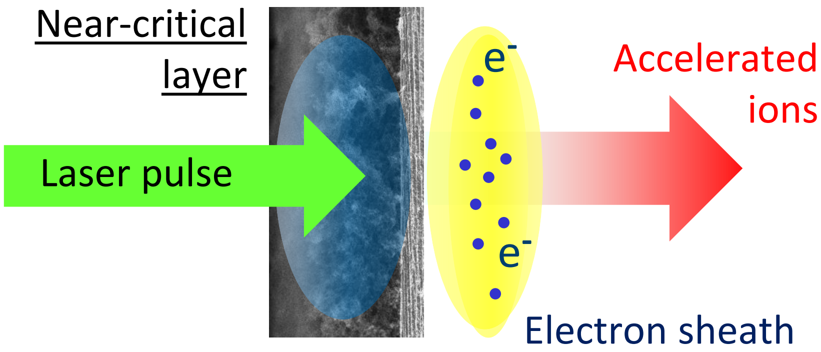
Novel applications to nuclear/materials science and engineering

Why foam-attached targets?

Conventional Target



Multi-layer, Foam-attached Target



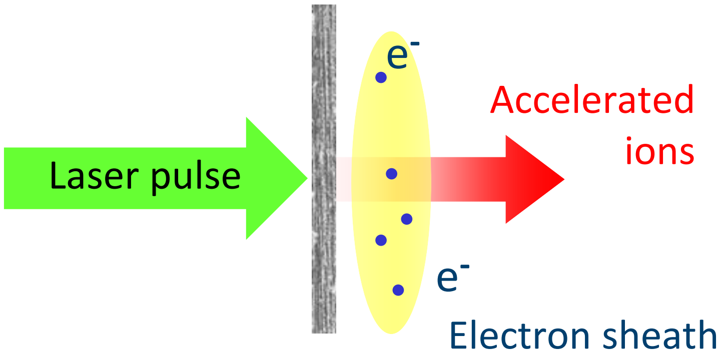
Micrometric thick solid foil
- ➢ Overdense plasma sheet
- ➢ **Surface interaction** mechanisms

Target Normal Sheath Acceleration (TNSA)

- Most investigated acceleration scheme
- Laminar, low emittance, Broad energy spectrum
- Scaling with I $>10^{22}$ W/cm^2 is unclear

Why foam-attached targets?

Conventional Target



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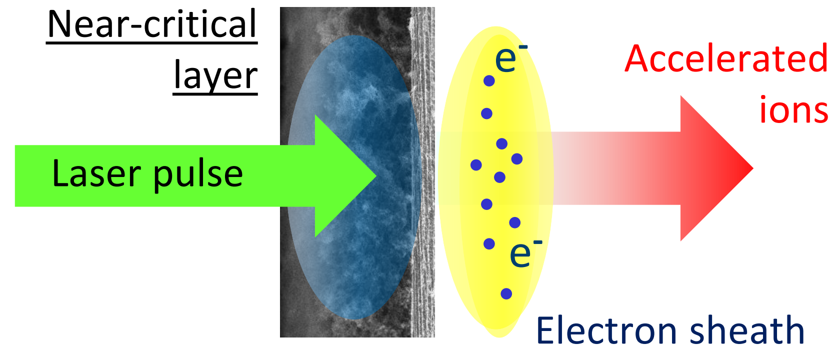


μm solid foil + **LOW DENSITY LAYER**

- ➢ **Near critical** plasma in front of the target:
- ➢ **Volume interaction** is possible

Enhanced TNSA:

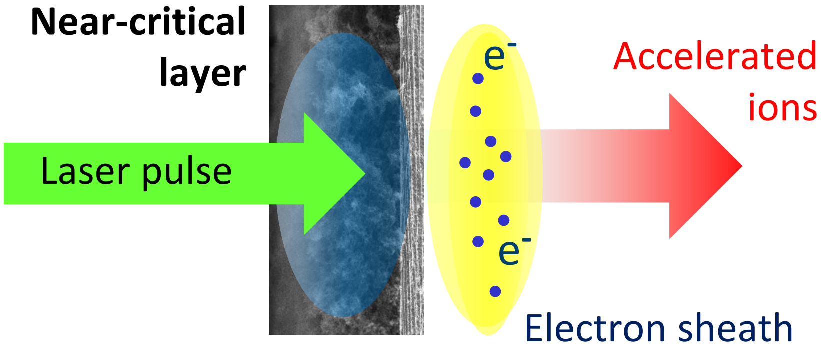
- Better coupling with the laser
- Enhanced fast electron production
- More ions and increased E_{max}

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

Foam-attached targets for Enhanced-TNSA

2D PIC simulations (ALaDyn code)

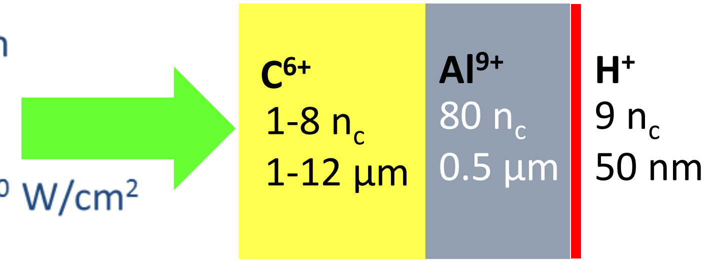
A. Sgattoni *et al.*, Phys. Rev. E, **85** 036405 (2012)



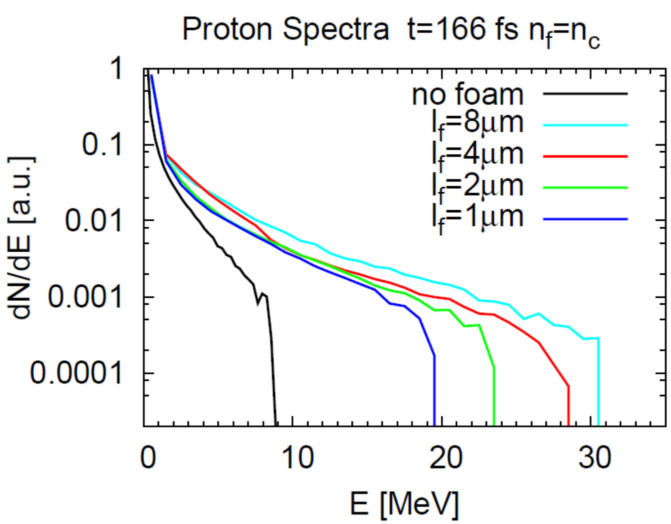
LASER PULSE

$\lambda = 0.8\ \mu m$
$\tau_L = 25\ fs$
$a_0 = 10$
$I_L \approx 2\times10^{20}\ W/cm^2$
$w_0 = 3\ \mu m$

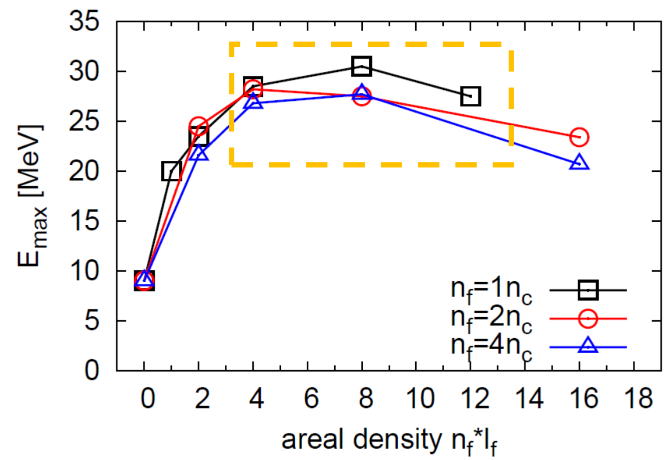
FOAM-ATTACHED TARGET



Enhanced E_{max} !



Foam optimization required



Quite challenging!

- $\rho < 10\ mg/cm^3$ (for $\lambda\approx1\ \mu m$)
- thickness from 5 to 10s µm

Production of carbon foams

PLD @ NanoLab

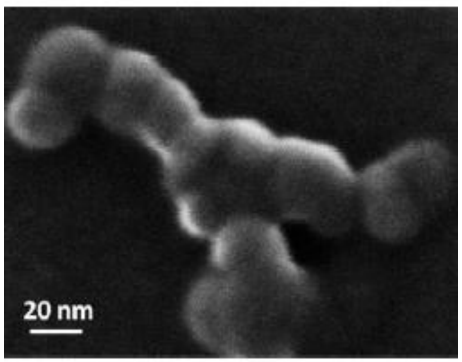
Foam property control

Laser fluence,
Gas pressure

Gas pressure,
Geometry

Geometry,
Process time

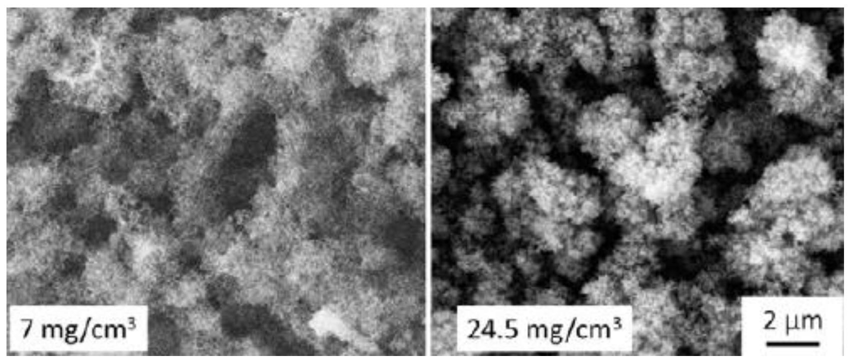
Nano-scale



Building blocks:
10 nm nanoparticles

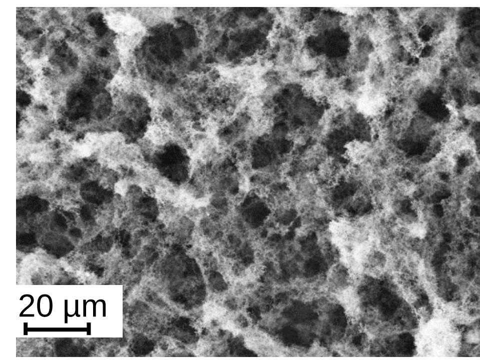
sp^2 network of
disordered domains

Micro-scale



Very open morphology
Tunable average density

Meso-scale



Good uniformity
Tunable thickness

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

Production of carbon foams

PLD @ NanoLab

Foam property control

Laser fluence,
Gas pressure

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Geometry

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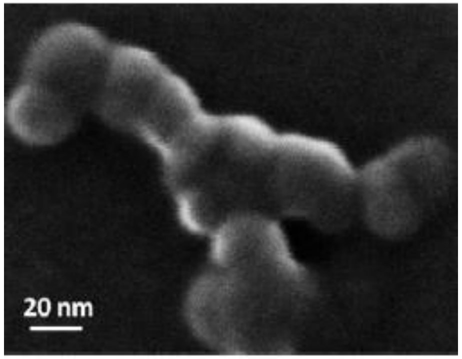
Process time

Nano-scale



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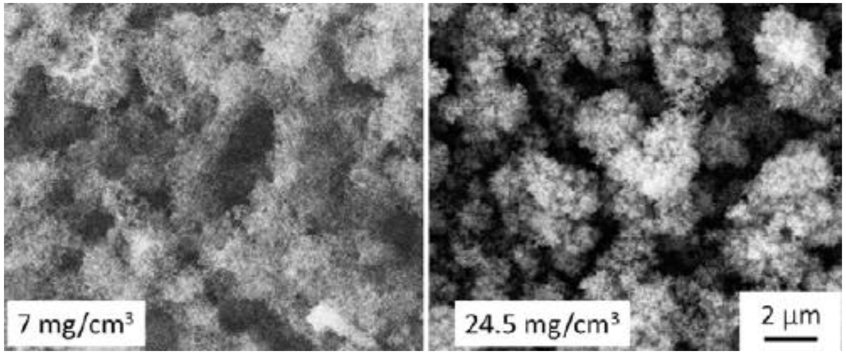
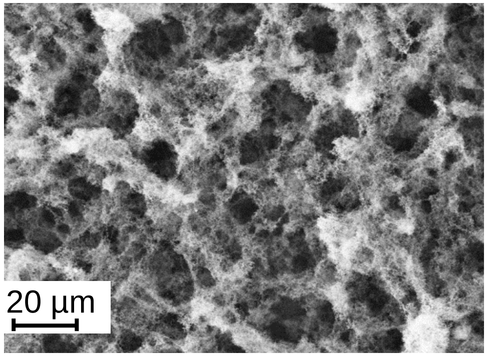


Very open morphology
Tunable average density

Meso-scale

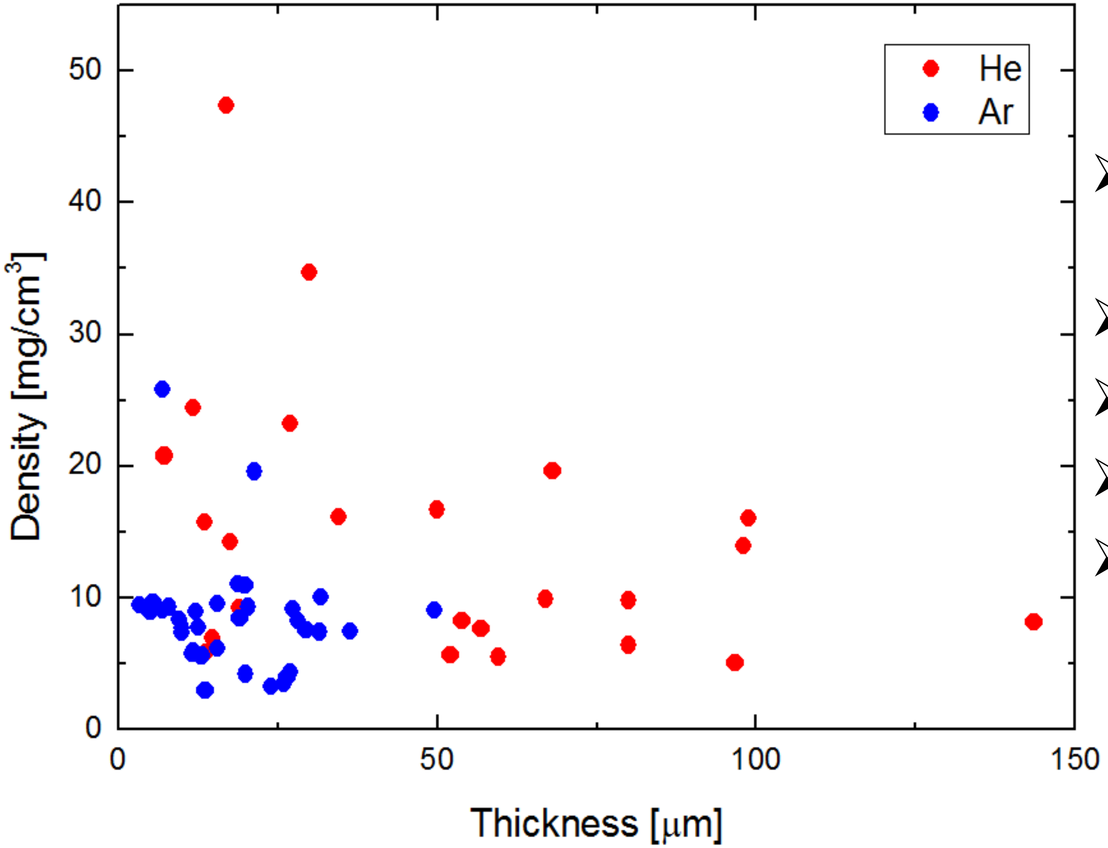


Good uniformity
Tunable thickness

Fine control of foam properties in a wide range of parameters!

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

Foam production capability



… moreover:

- Good substrate **coverage** down to 3-6 μm
- Good **reproducibility**
- **Flat** thickness profile
- Growth on **every substrate**
- (reletively) **robust and easy** to transport!

PLD @ NanoLab

- Density down to 3 mg/cm^3
- Thickness from 2 to 150 μm

Possibility to match the **requirements** for enhanced ion acceleration

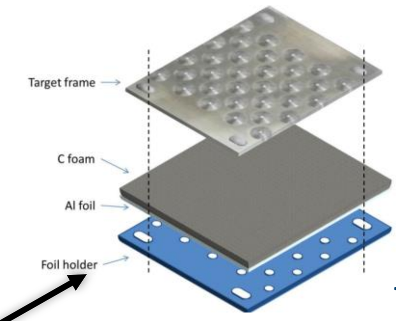
Acceleration experiment @ PULSER I - GIST

in collaboration with:

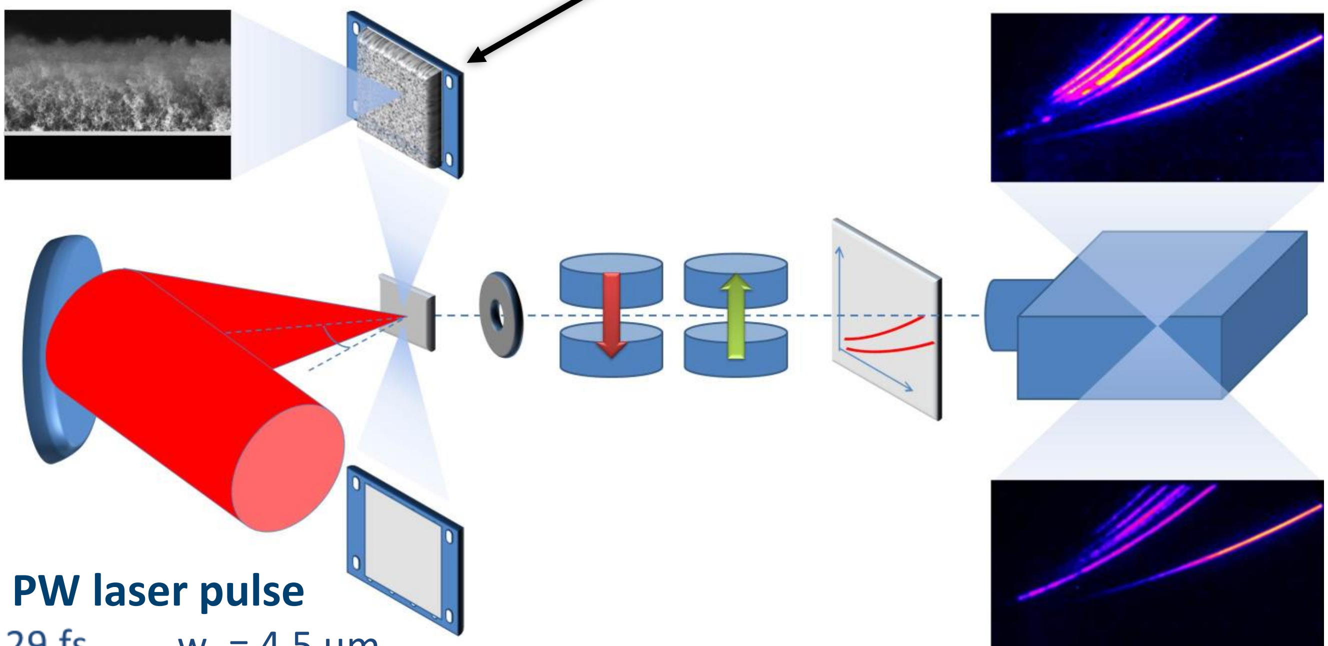
Foam-attached targets

Al foil 0.75 µm – 1.5 µm

C foam 8 – 36 µm @ 6.8 mg/cm^3;
12 µm @ 24.5 mg/cm^3



Thomson parabolas



1 PW laser pulse

τ_L = 29 fs w_0 = 4.5 µm
λ = 0.79 µm α=30°
E_L= 1 – 8 J 10^{11} contrast

Intensity scan ($I_L > 5 \times 10^{19}$ W/cm^2) for:

- **bare Al** and different **foam-based** targets
- circular, p- and **s-polarization**

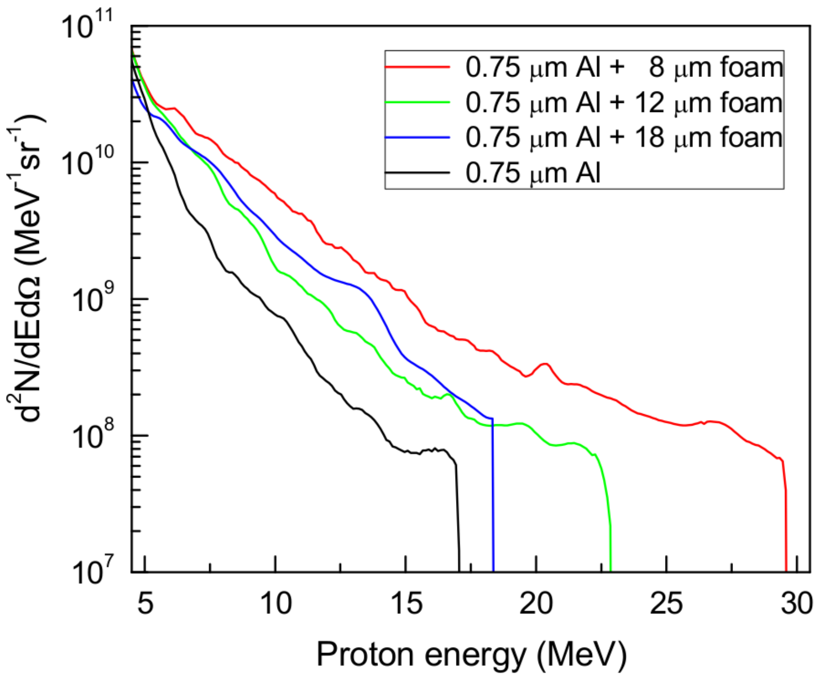
Acceleration experiment @ PULSER I GIST

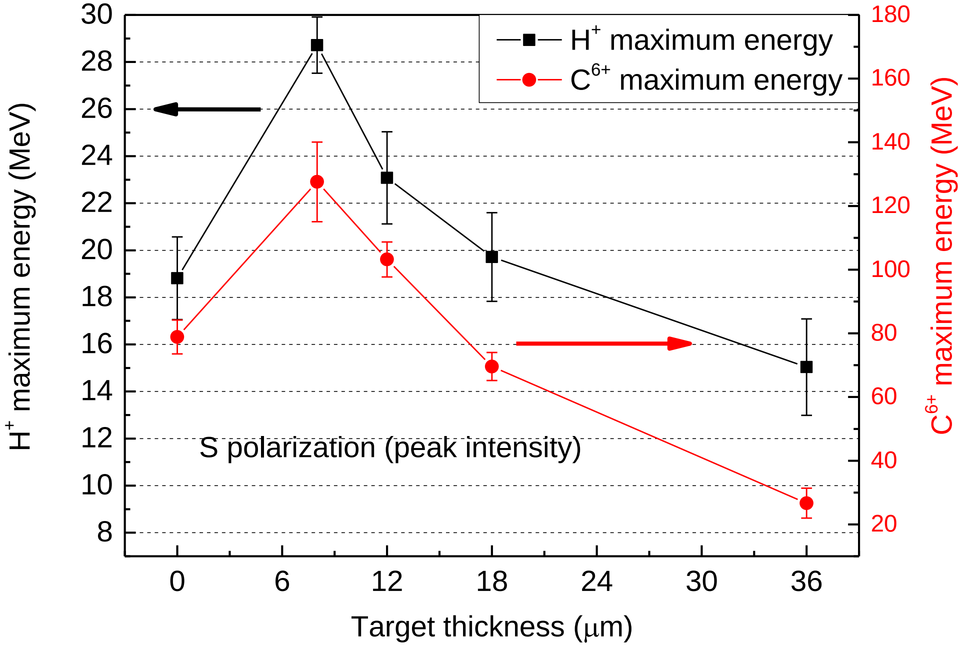
NanoLab

in collaboration with: GIST

Laser properties: s-polarization, full power → 4×10^{20} W/cm^2

Nearcritical foam: Al (0.75 µm) + foam (6.8 mg/cm^3, 0-36 µm)





- ↑ number of fast protons [gain factor 7.3 above 5 MeV]
- ↑ E_{max} H^+: 30 MeV [vs 18 MeV]
- ↑ E_{max} C^{6+}: 130-140 MeV [vs 80 MeV]

Systematic enhancement!

M. Passoni *et al.*, Plasma Phys. Control. Fusion, **56** 045001 (2014)

Acceleration experiment @ PULSER I GIST

NanoLab

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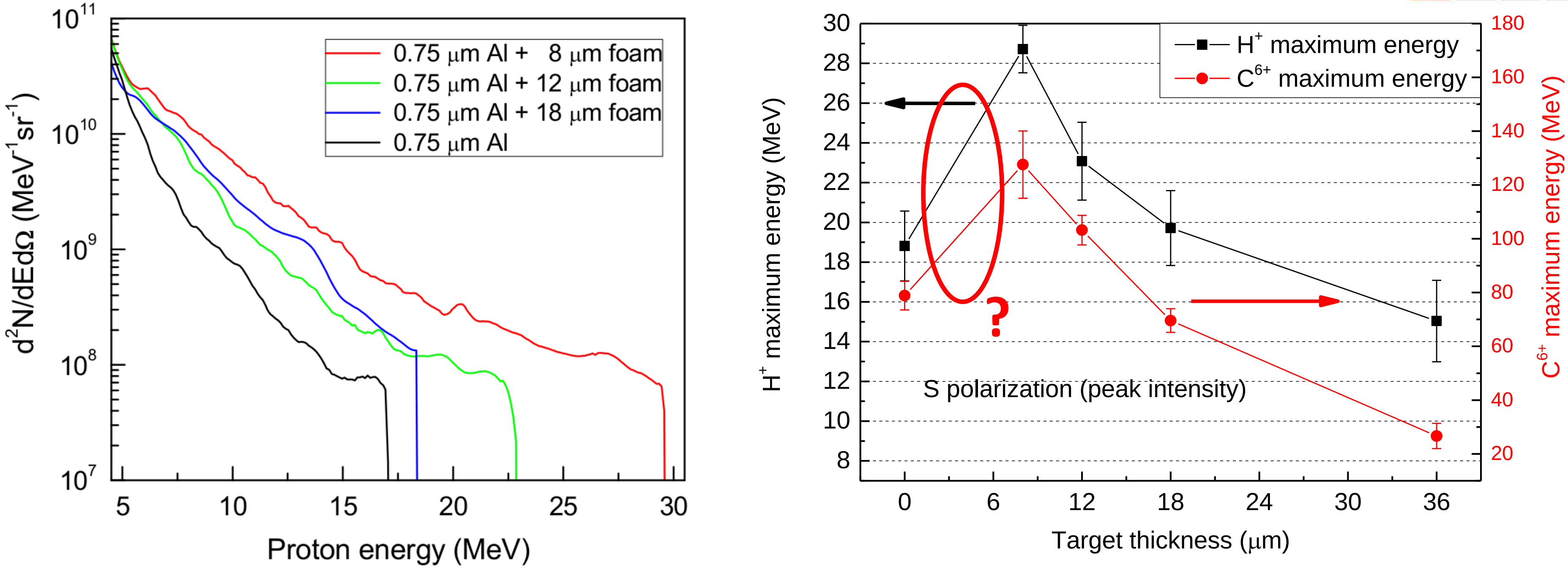

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Systematic enhancement!

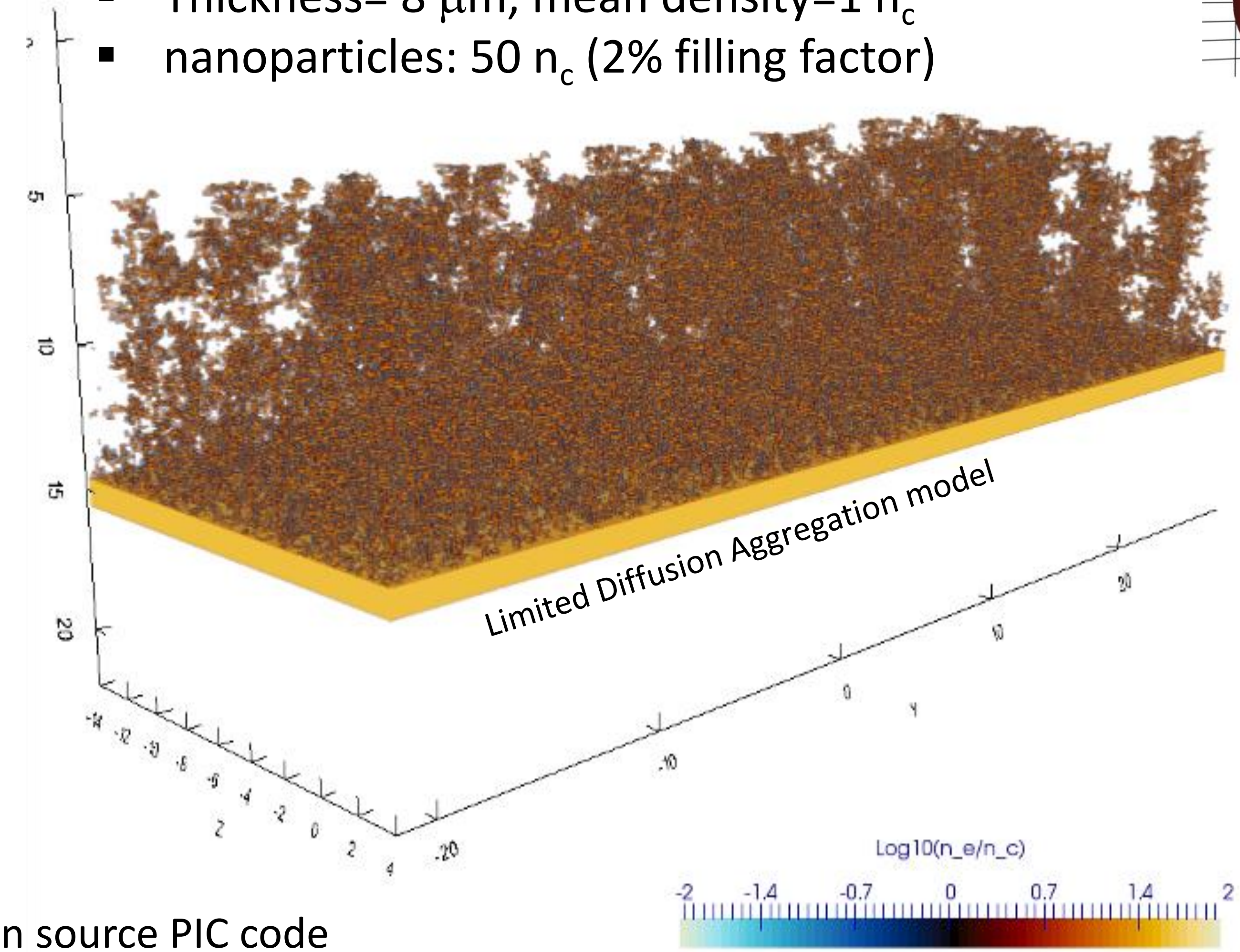
Thinner foams?

M. Passoni *et al.*, Plasma Phys. Control. Fusion, **56** 045001 (2014)

3D PIC simulation of nanofoam irradiation

t = 0 τ_p

- I = $7x10^{20}$ Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

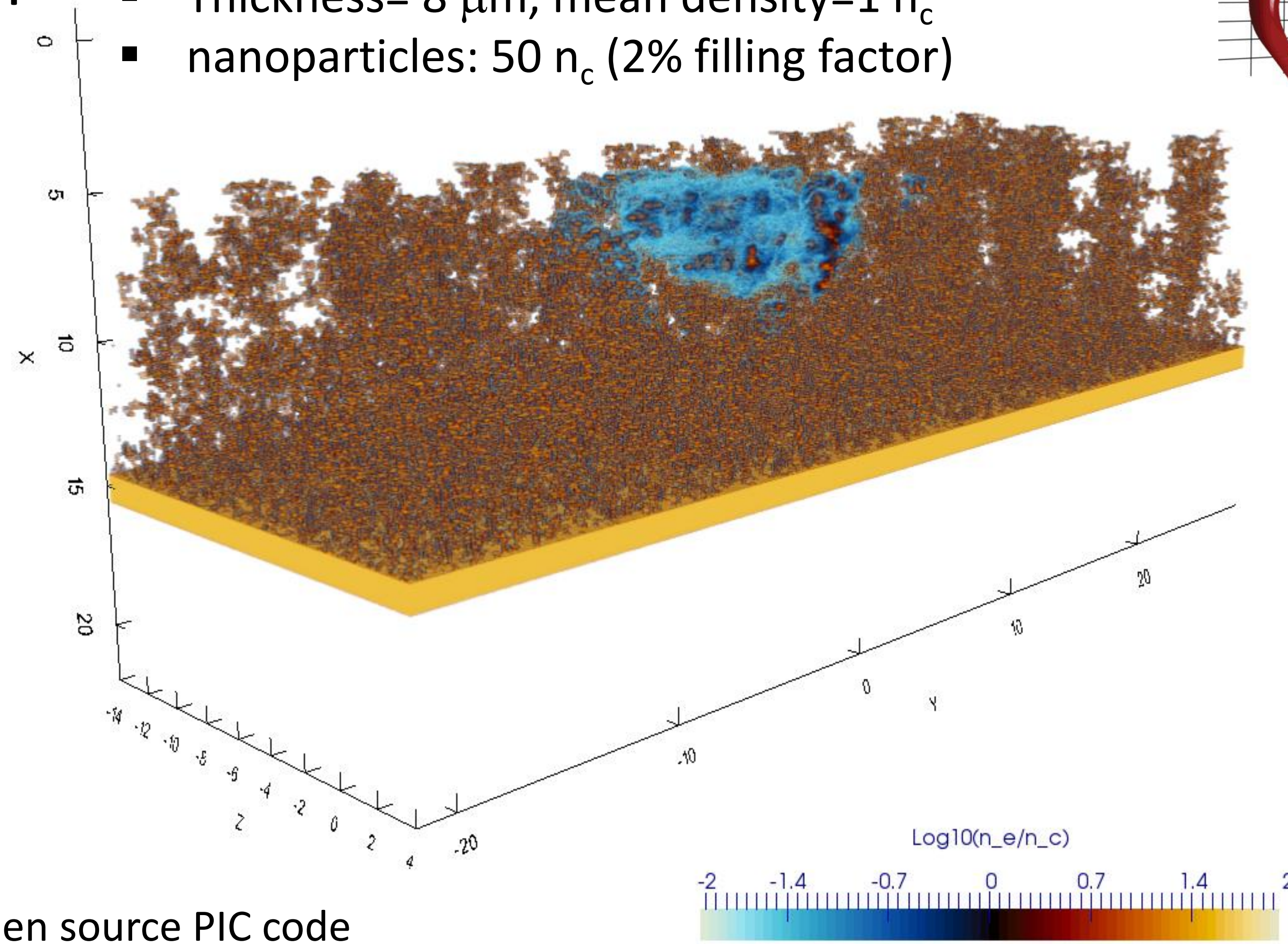


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 4 τ_p

- I = 7×10^{20} Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

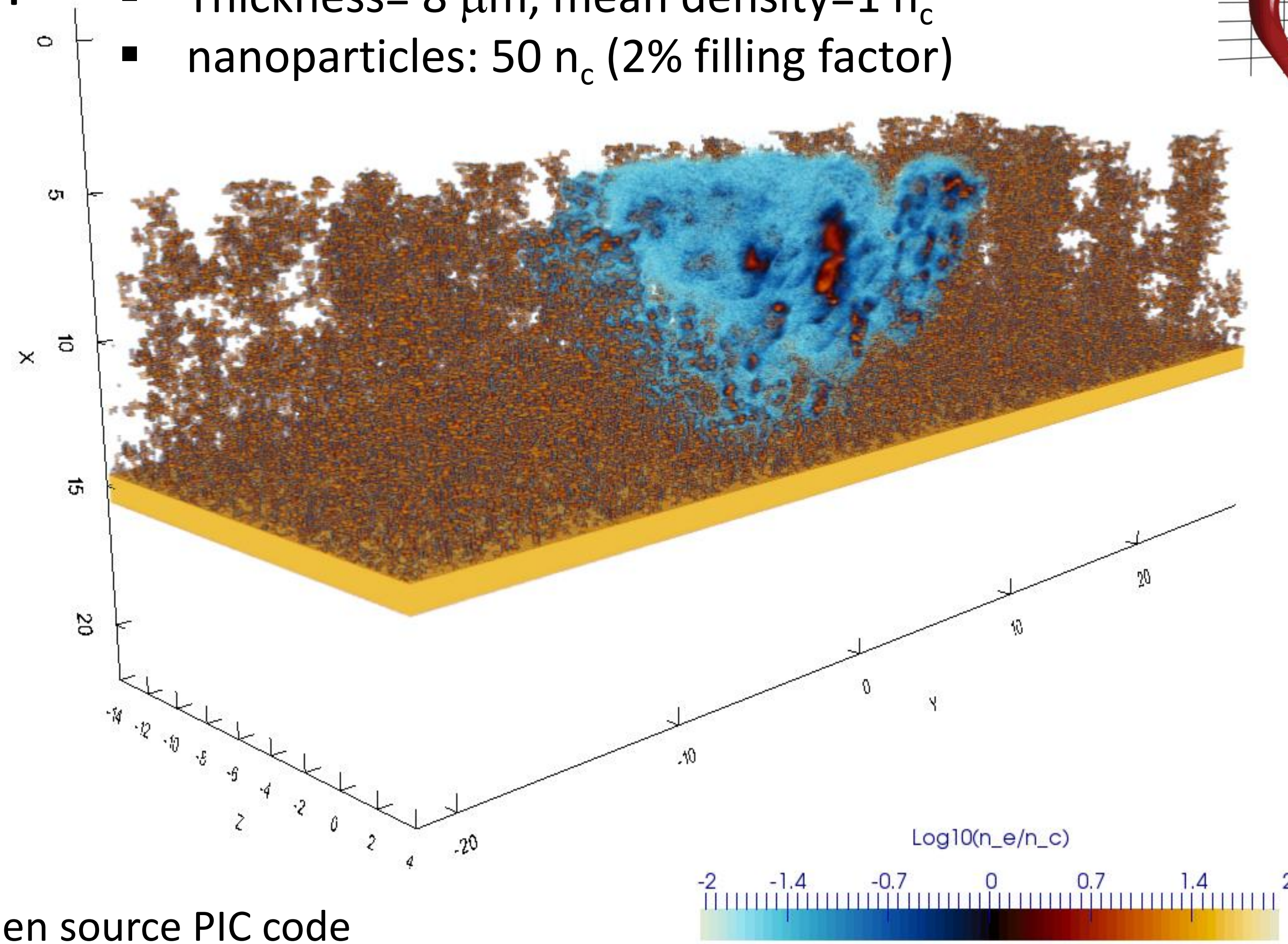


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 8 τ_p

- I = 7×10^{20} Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)



Piccante open source PIC code
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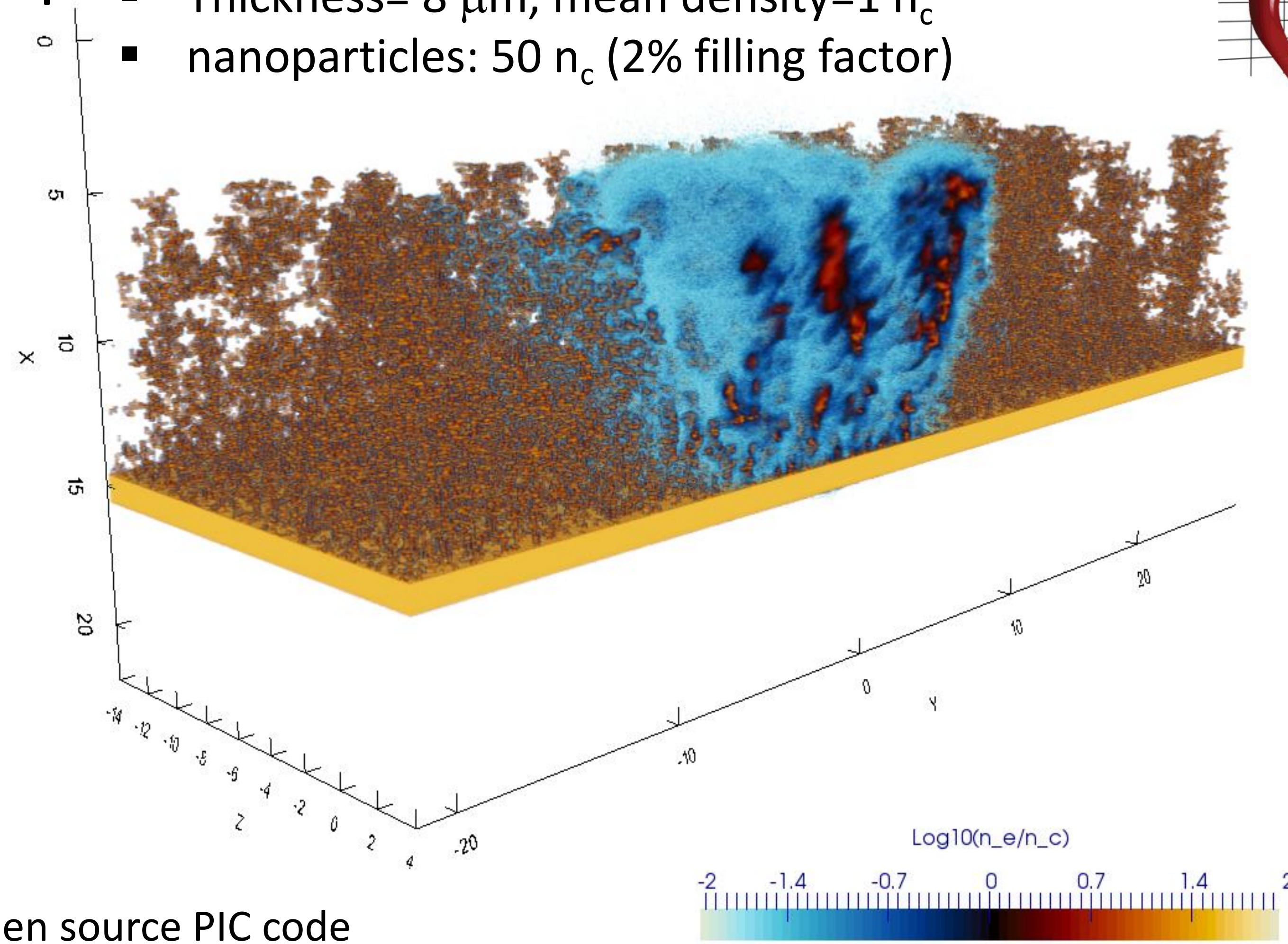
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 12 τ_p

- I = 7×10^{20} Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

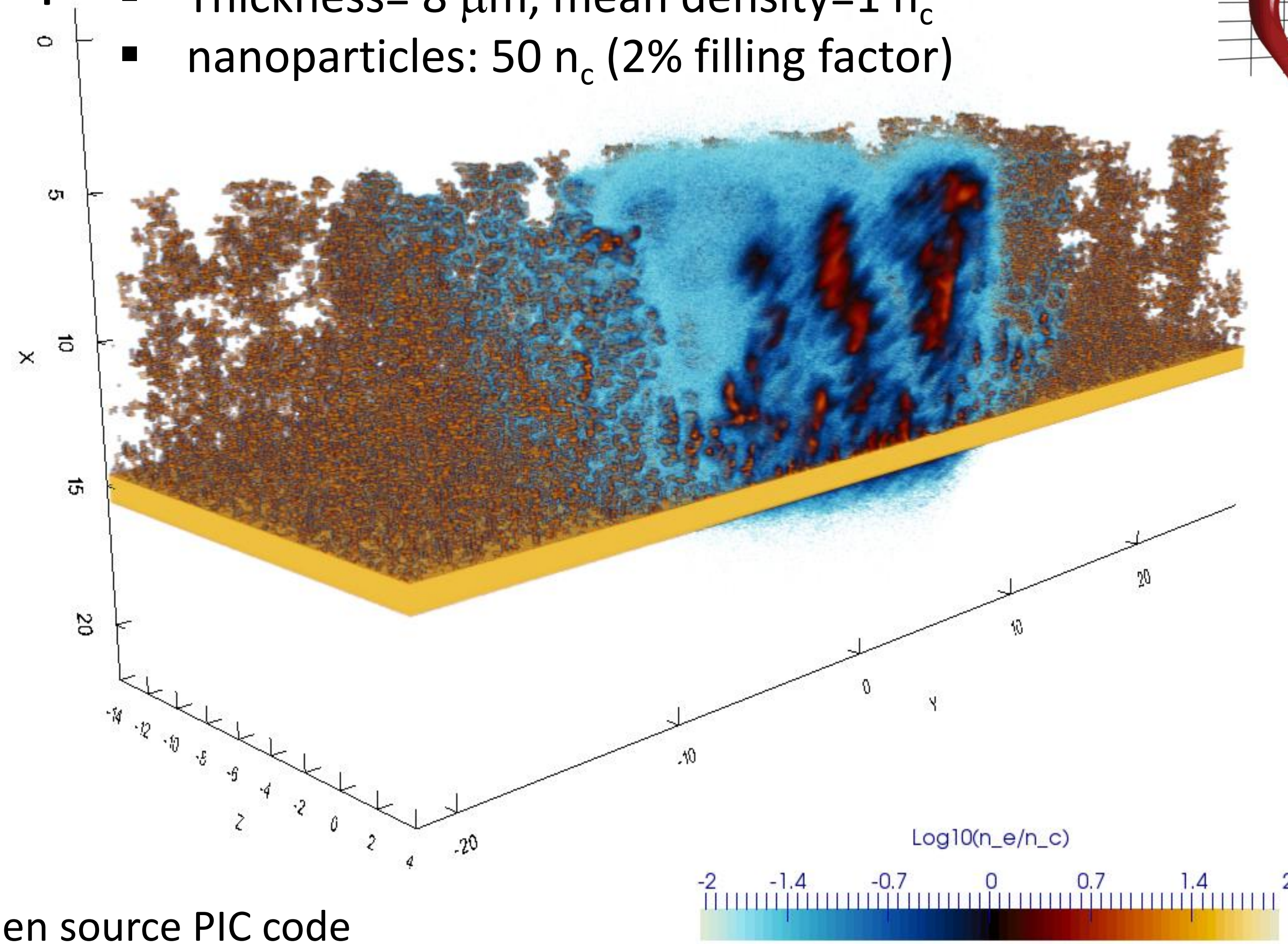


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 16 τ_p

- $I = 7 \times 10^{20}$ Wcm^{-2} $\tau_L = 33$ fs, $\alpha = 30°$
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

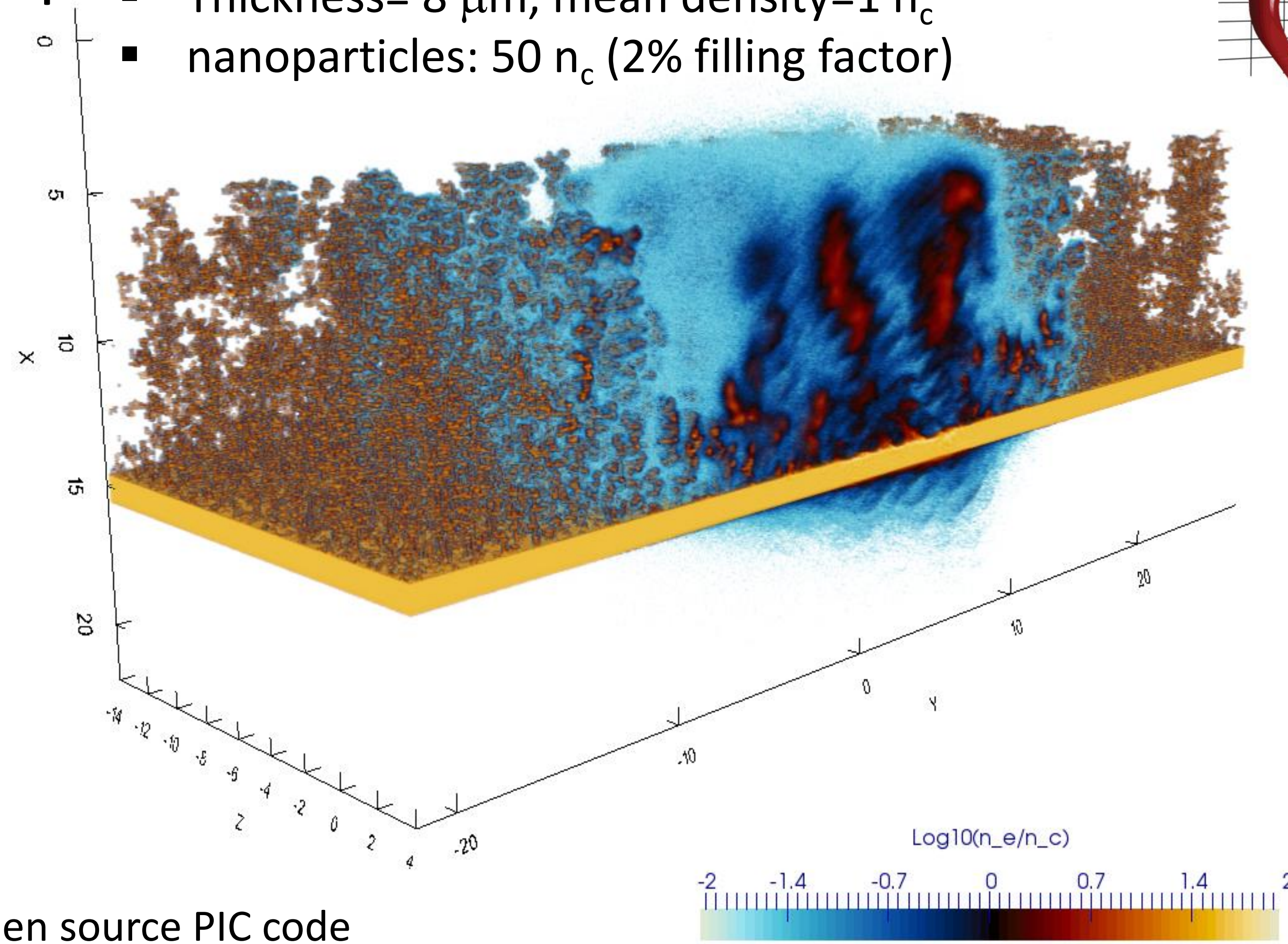


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 20 τ_p

- I = 7×10^{20} Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

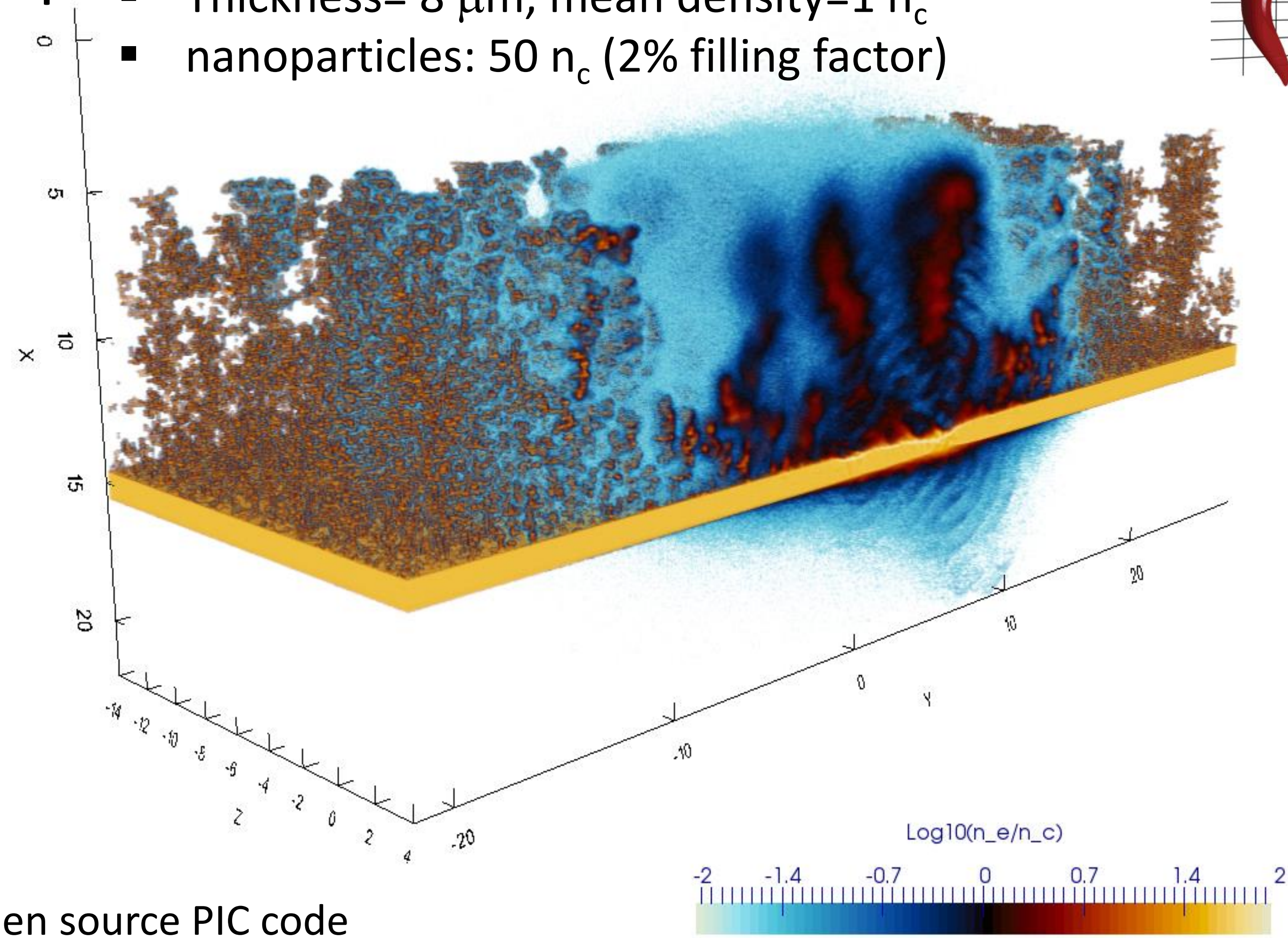


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 24 τ_p

- I = 7×10^{20} Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

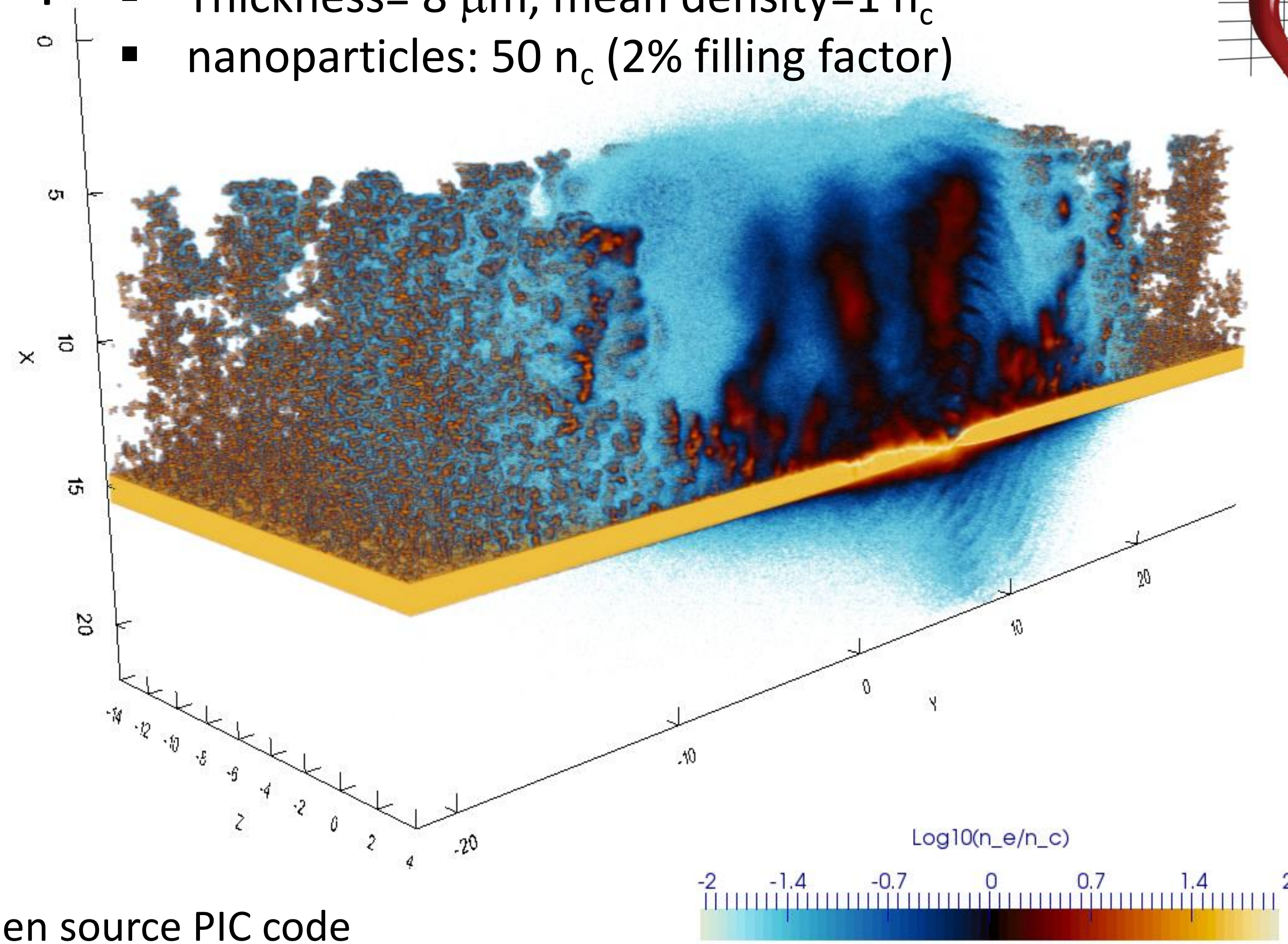


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 28 τ_p

- I = 7×10^{20} Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

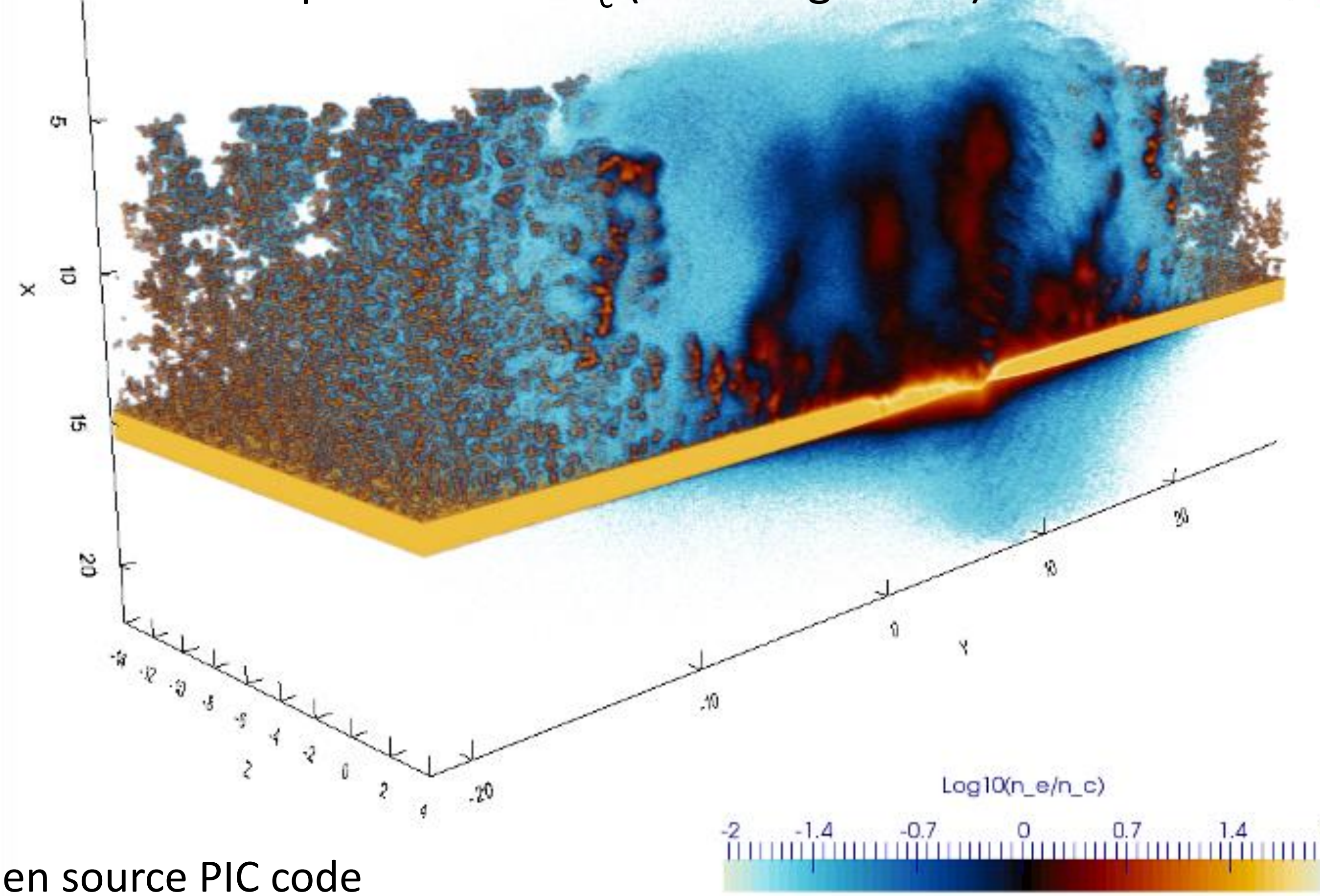


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

$t = 32\ \tau_p$

- $I = 7 \times 10^{20}$ Wcm^{-2} $\tau_L = 33$ fs, $\alpha = 30°$
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)

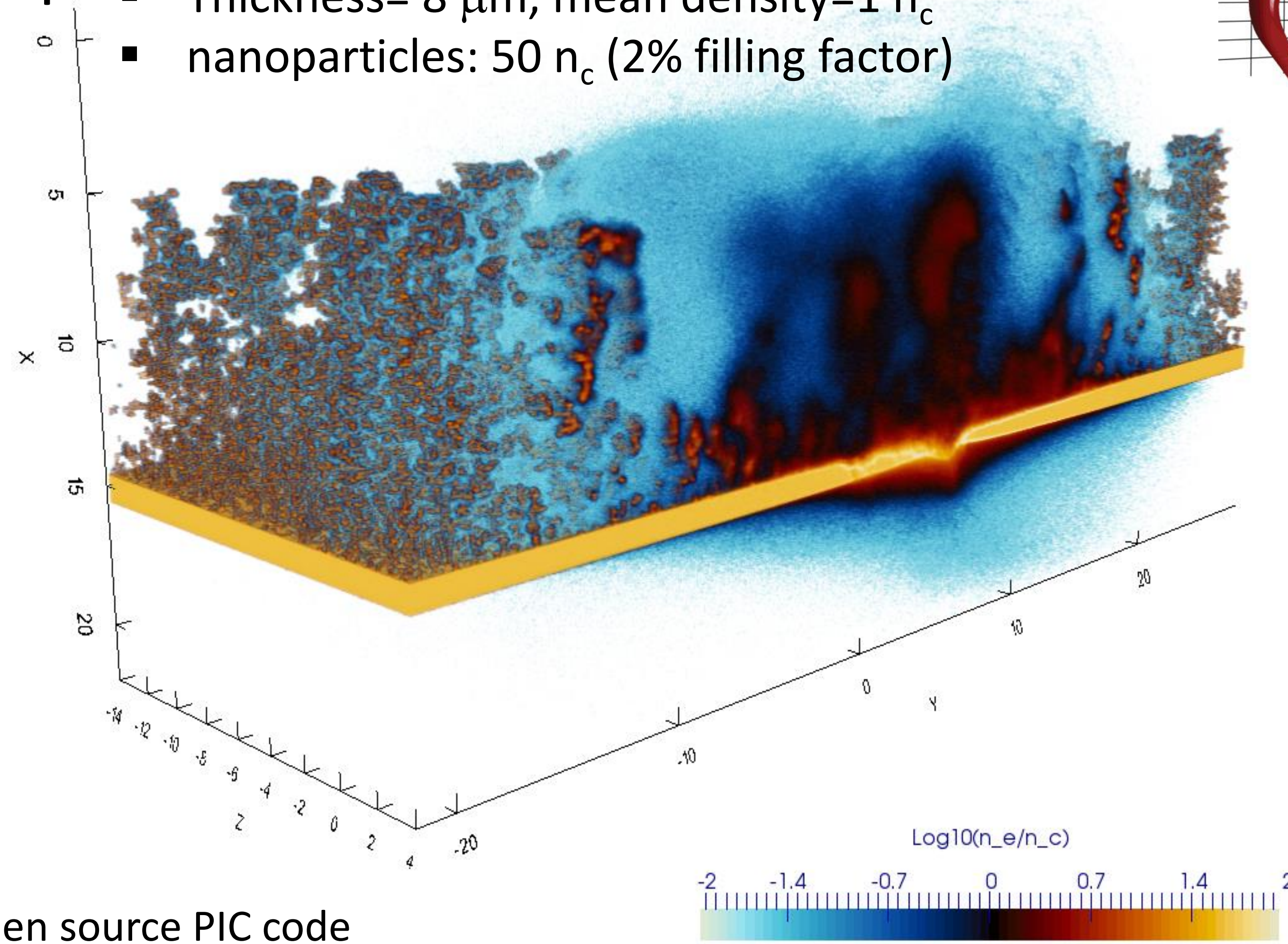


Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

t = 36 τ_p

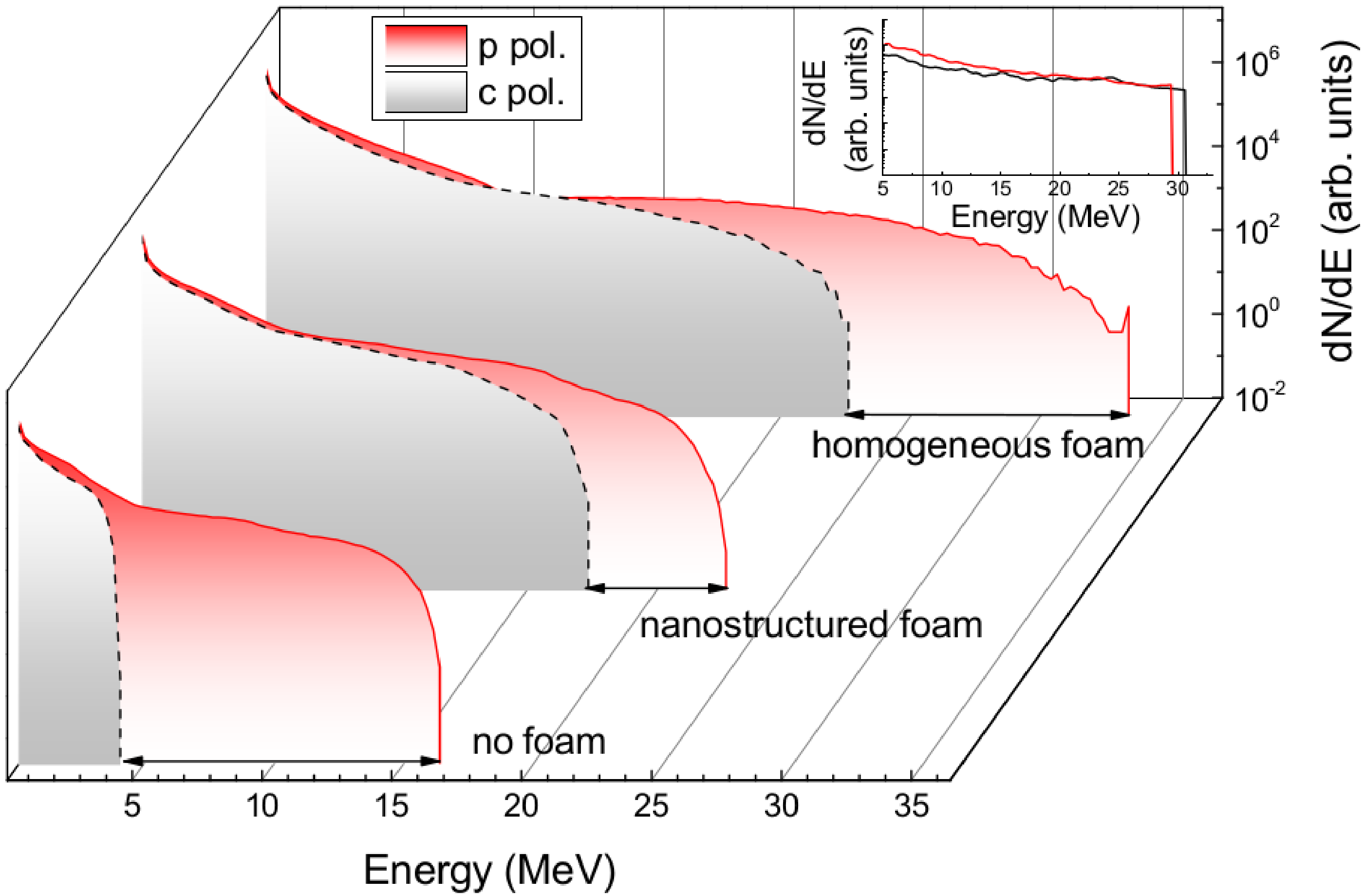
- I = 7×10^{20} Wcm^{-2} τ_L = 33 fs, α = 30°
- Thickness= 8 μm, mean density=1 n_c
- nanoparticles: 50 n_c (2% filling factor)



Piccante open source PIC code
http://aladyn.github.io/piccante/
Sgattoni, Fedeli, Sinigardi, Marocchino

3D PIC simulation of nanofoam irradiation

NanoLab



piccante Open Source PIC Code

Higher energies with more homogeneous foam:

…There is room for optimization!

Micro- and nanostructured materials

First wall materials and components for magnetic fusion

- Functional coatings (Rh, W)
- Mimicking of re-deposited/ irradiated materials

Advanced targets for laser driven ion acceleration

- Carbon foams with near critical density
- Enhanced ion acceleration

Future perspectives:

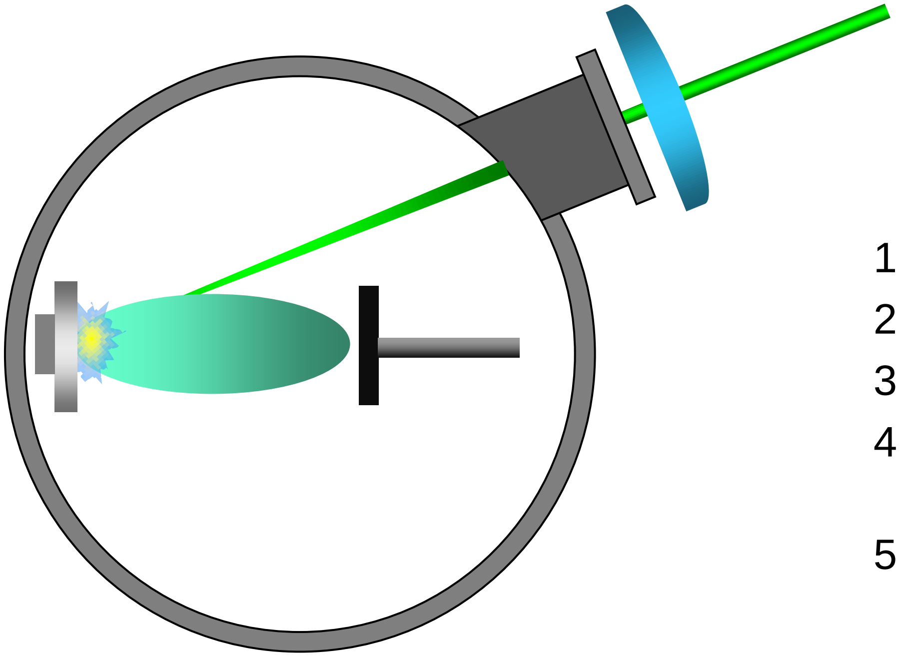
- Further optimization (e.g. gradient foams, free standing foils)
- Experimental validation (tokamak/laser facilities)
- Ready to explore novel applications!

Thank you!

Thank you for your attention!

Additional slides

Pulsed Laser Deposition



Schematic of PLD process:

1. Pulsed laser focused on solid target
2. Target ablation and plume formation
3. Plasma plume-laser interaction
4. Plume expansion (vacuum or gas background)
5. Deposition on a substrate, E_{at}≈1-100 eV

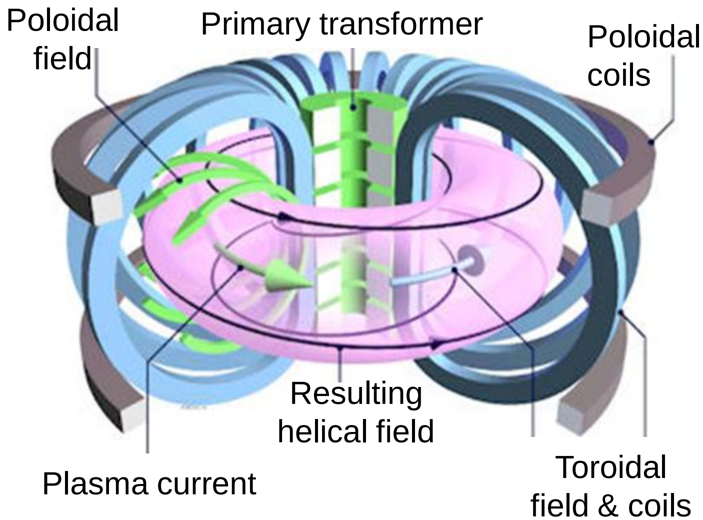
Film nanostructure can be controlled through:

- Laser fluence
- Background pressure
- Target to substrate distance/geometry

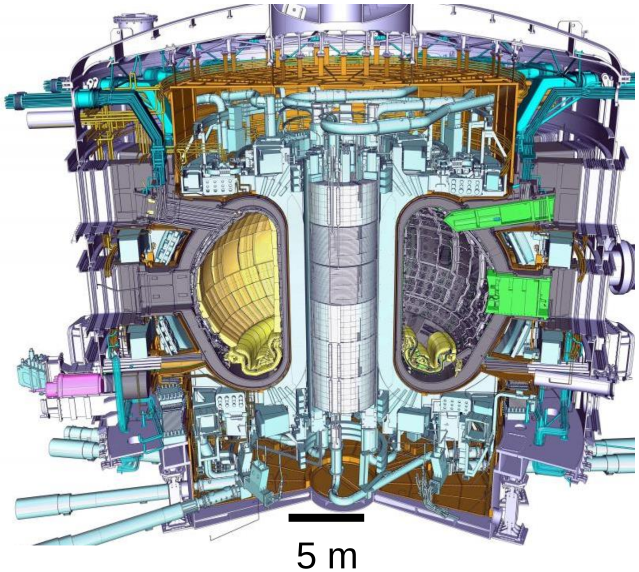
PLD features: Multiscale control of material properties
Area cm^2, thickness mm

Magnetic confinement fusion

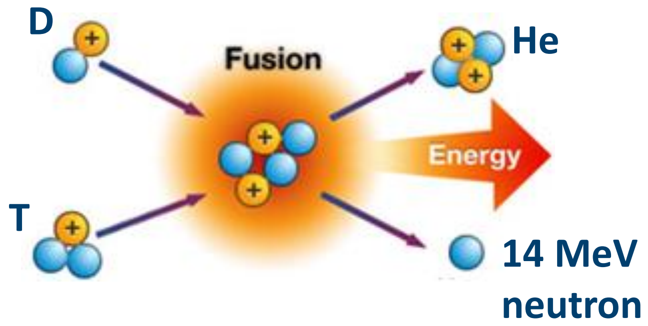
Tokamak concept:



ITER



D-T plasma confined with **magnetic fields**:



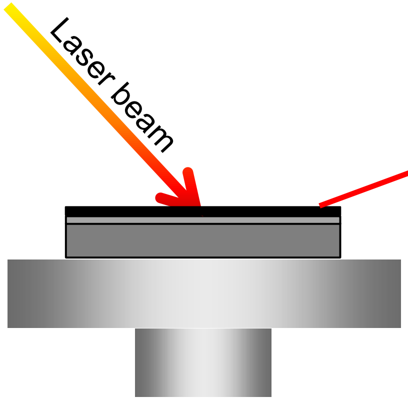
- **T = 10^8 K**
- **n ~ 10^{14} nuclei/cm³, τ_E ~ seconds**

Laser cleaning of diagnostic mirrors

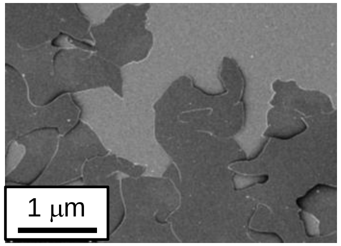
A. Maffini, et al. J. Nucl. Mater. 463 (2015) 944–947

Laser pulses parameters

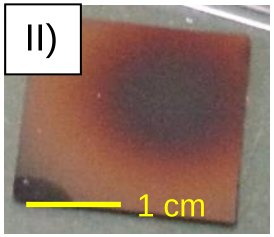
- 60 pulse per site, λ=1064 nm
400 mJ/cm^2

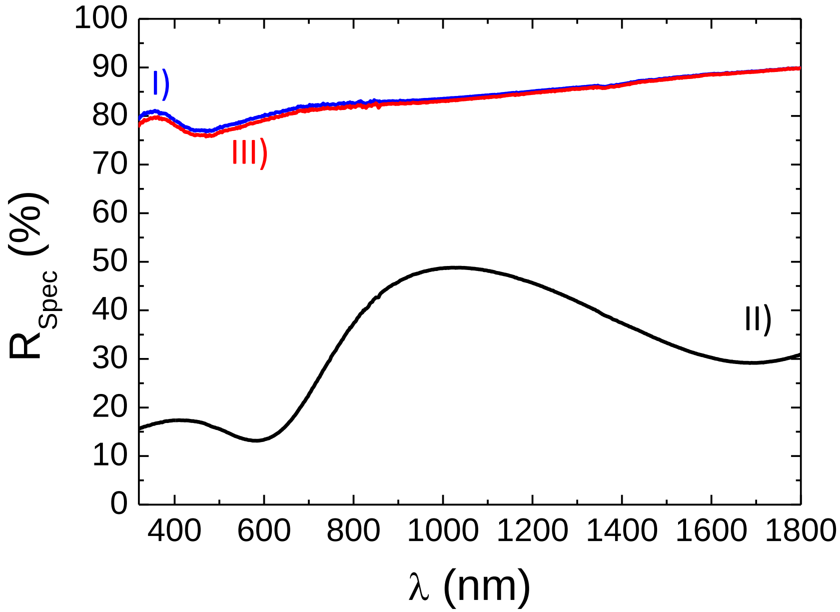


C compact film

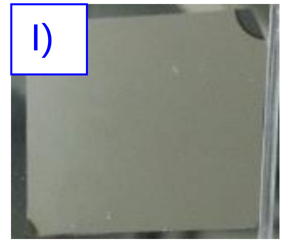


C/Rh before cleaning

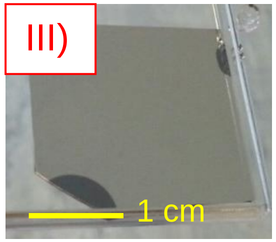




Rh film as deposited



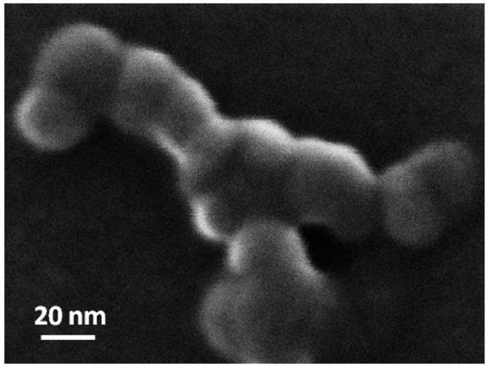
C/Rh, IR cleaning



- Satisfactory R_{Spec} recovery over all analyzed wavelength range
- C films with different morphologies to demonstrate effectiveness and robustness of developed laser cleaning procedure

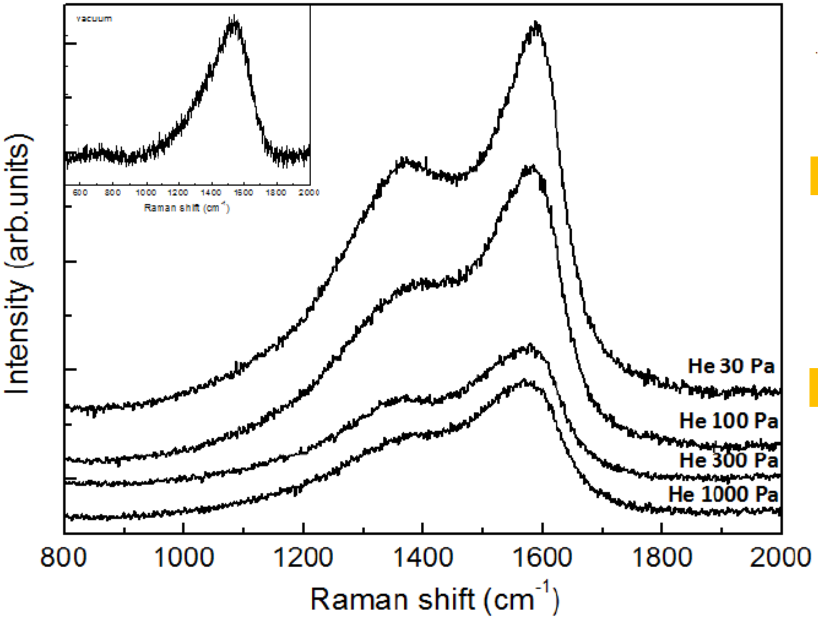
Nanoscale analysis

Scanning Transmission Electron Microscopy



Elementary consituents:
10-20 nm nanoparticles

Raman spectroscopy

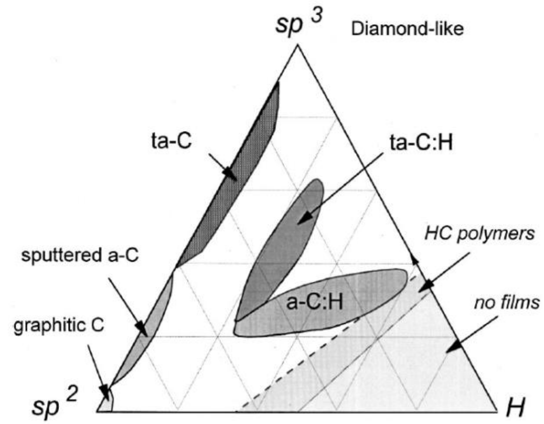


Nearly pure sp^2 network of topologically disordered domains :
odd-membered rings and few chain-like structures

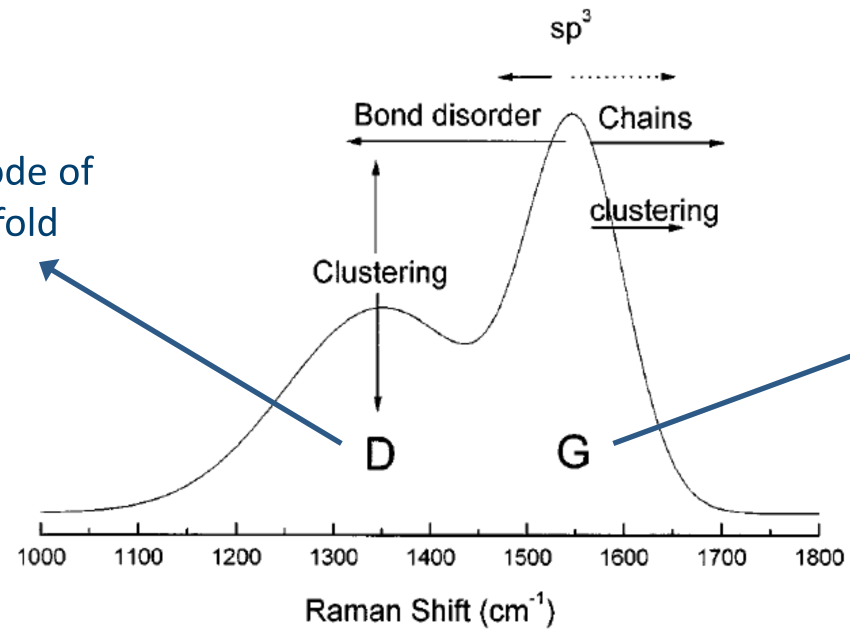
Ordered graphitic domains dimension ~ 2nm

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

- 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



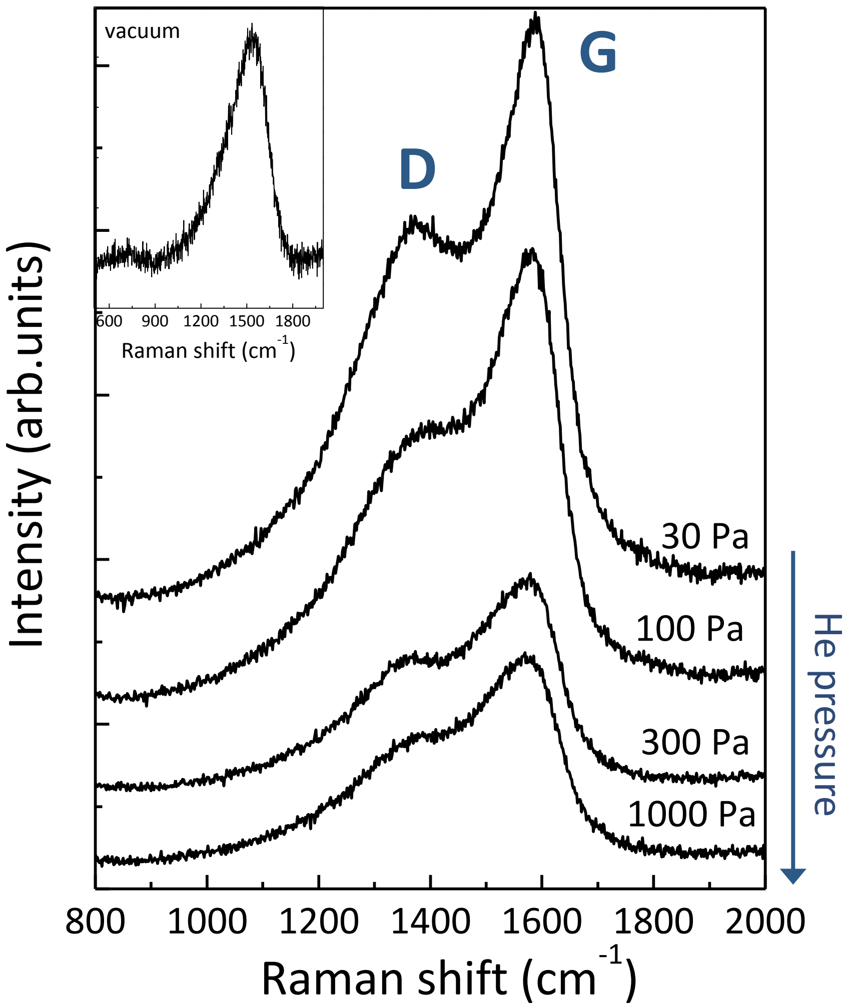
Breathing mode of aromatic six-fold rings



stretching mode of sp^2 C-C pair

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

PLD carbon foams: Raman spectroscopy

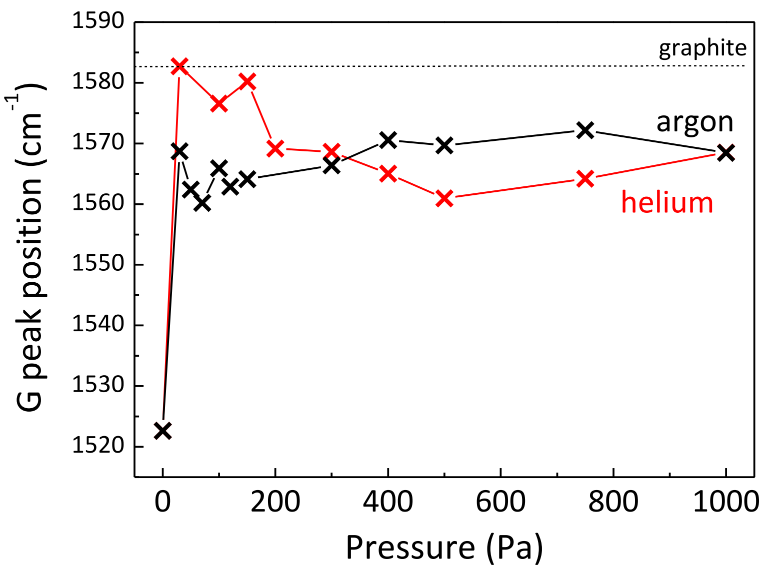


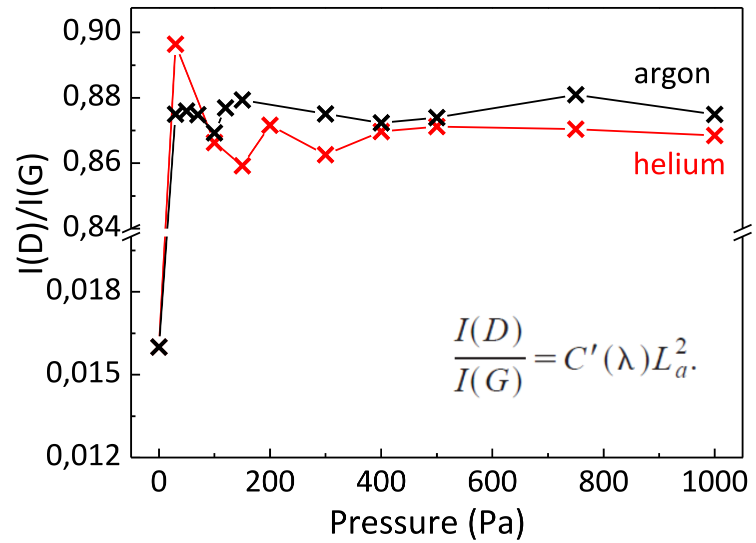
- Similar Raman spectra, typical of a-C, at any pressure, both for argon and helium
- Some differences in peak positions and relative intensities
- Fitting procedure
  - Asymmetric Breit-Wigner-Fano (BWF) function for G peak
  - Lorentzian function for D peak

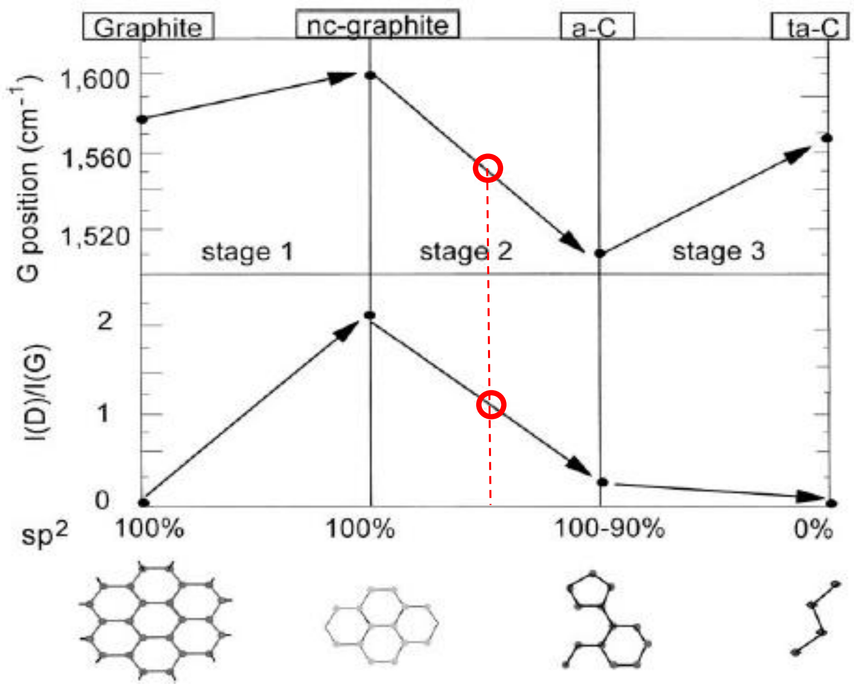
[Ferrari AC, Robertson J, Phys. Rev. B 61 (2000) 14095]

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

Raman spectra interpretation







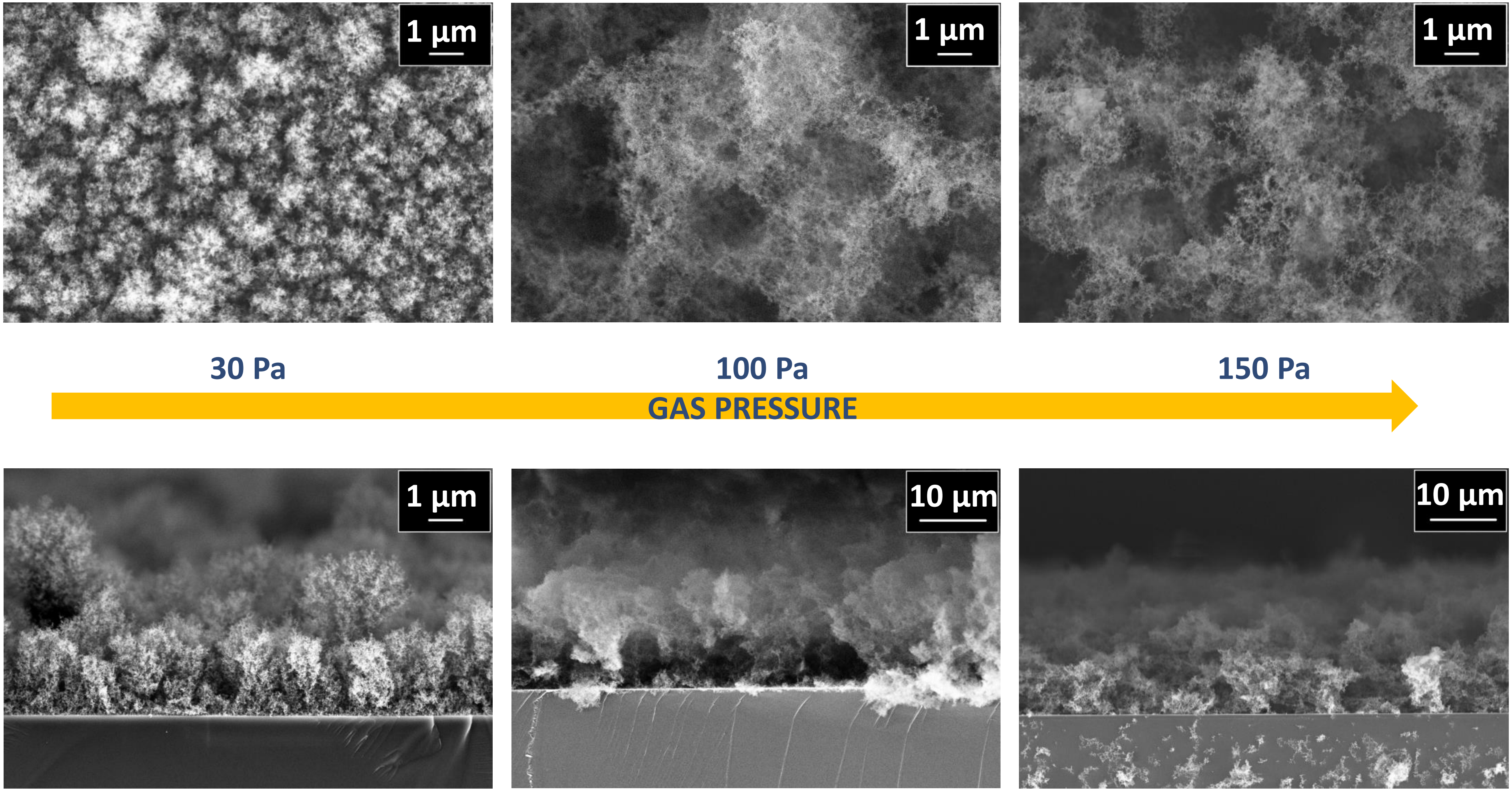
[Robertson J, Mat. Sci.&Eng R 37 (2002) 129]

- 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)

Morphological analysis

Scanning Electron Microscopy

Argon

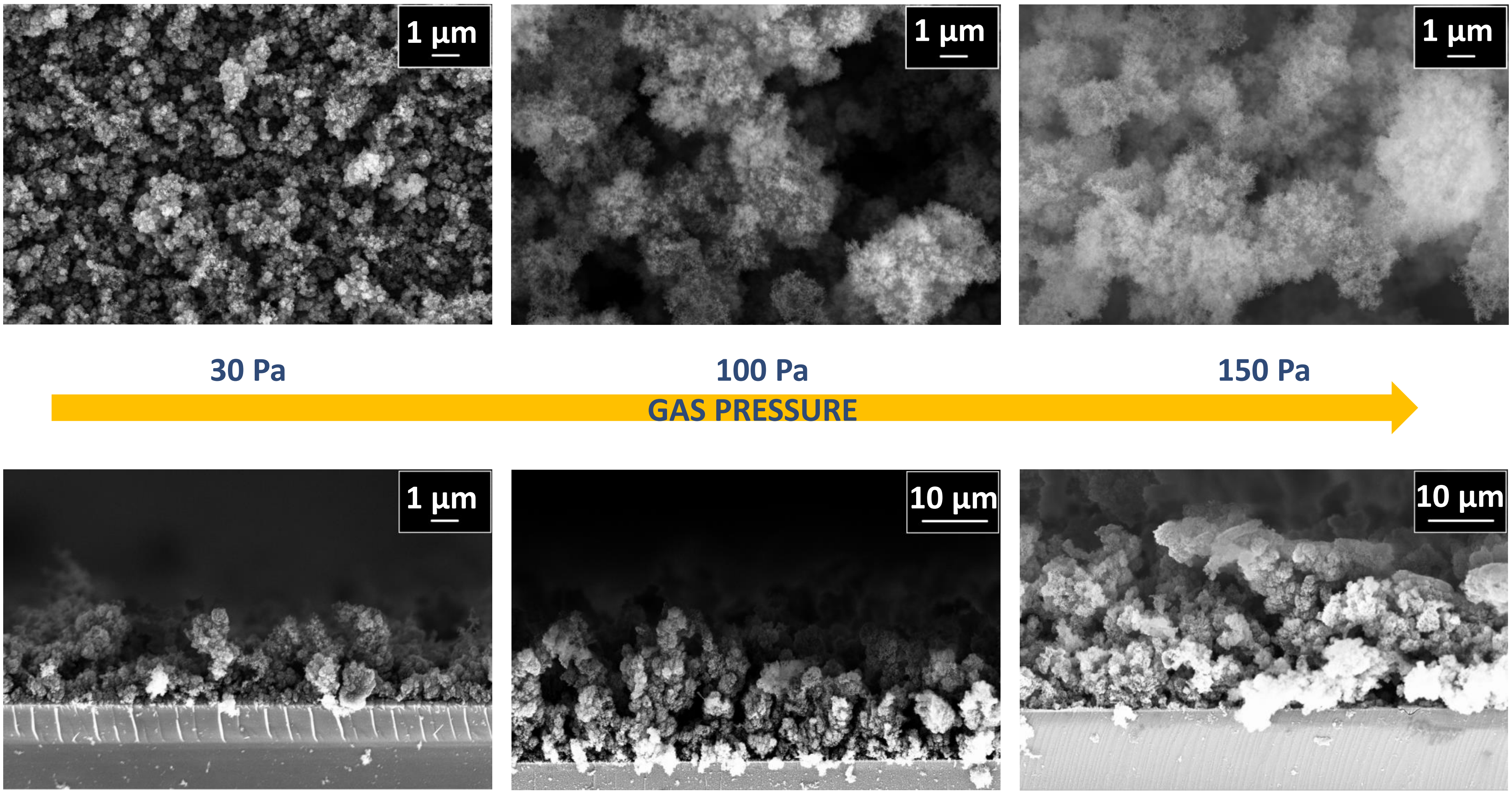


Target-substrate distance 8.5 cm, deposition duration 20 min

Morphological analysis

Scanning Electron Microscopy

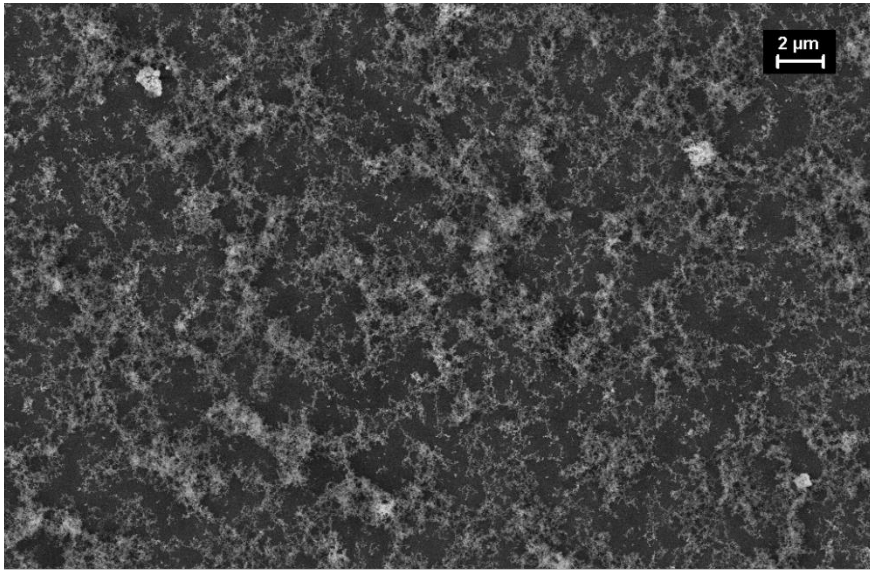
Helium



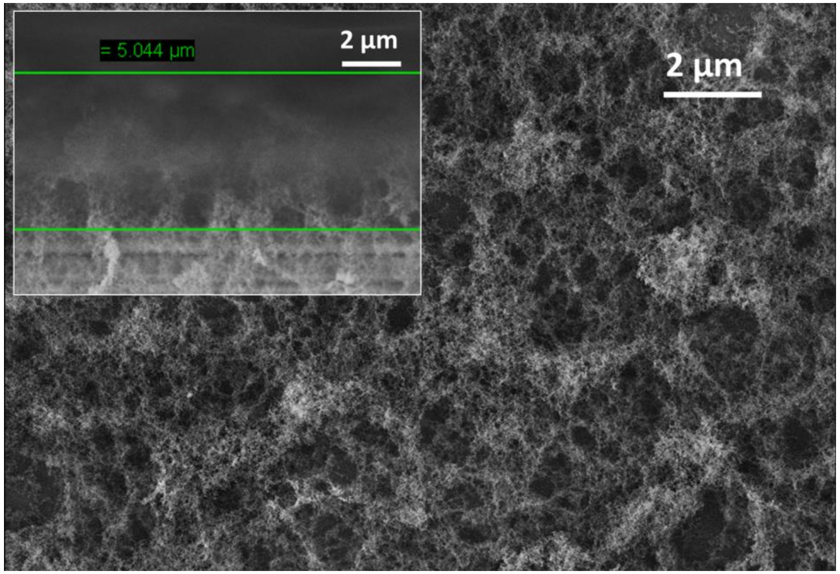
Target-substrate distance 8.5 cm, deposition duration 20 min

Substrate coverage for thin foams

Problem:
incomplete substrate coverage below 10 μm



Solution: target-substrate distance
- ↘ better foam packing
- ↘ lower characteristic dimension of the «foam net»
- ↘ higher deposition rate
- ↘ higher density ⟶higher P required



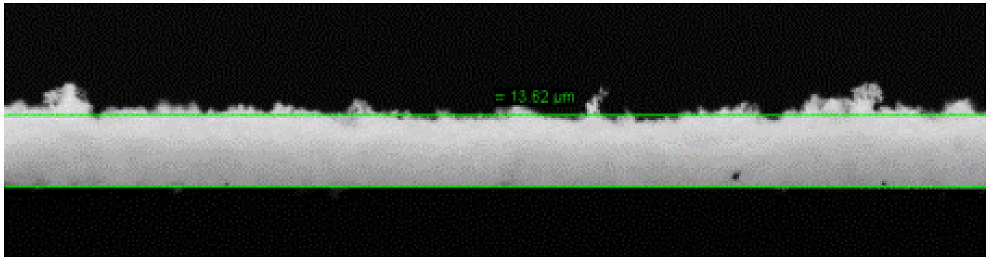
Density measurement

Thickness assessment

Areal density measurement

→ **DENSITY EVALUATION**

Thickness assessment: cross-sectional SEM images



Areal density measurement

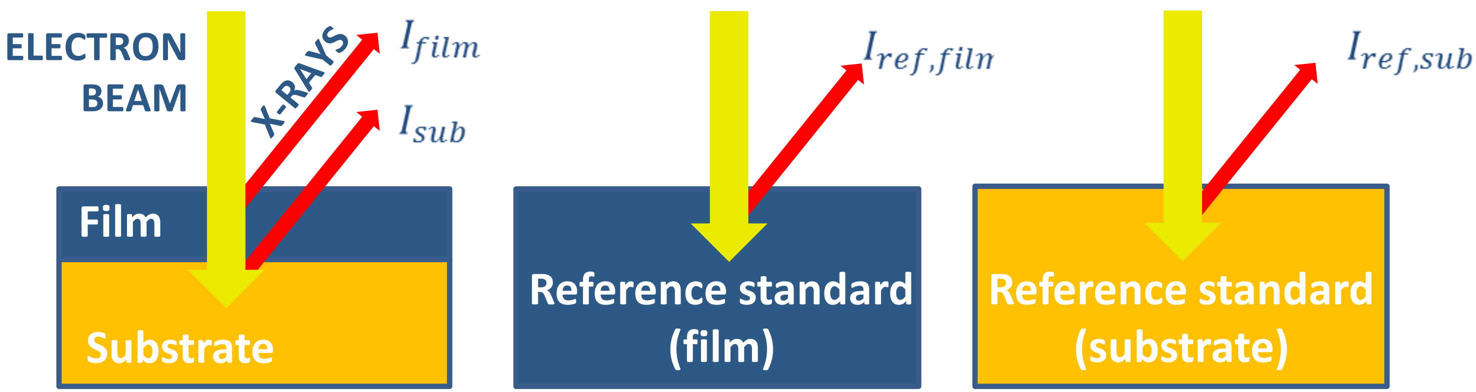
Conventional quartz-crystal microbalance (QCM) technique unreliable for densities under 20 mg/cm^3

technique based on

Energy Dispersive X-Ray Spectroscopy (EDS)

Areal density evaluation

Energy Dispersive X-ray Spectroscopy (EDS)



TWO APPROACHES FOR AREAL DENSITY CALCULATION

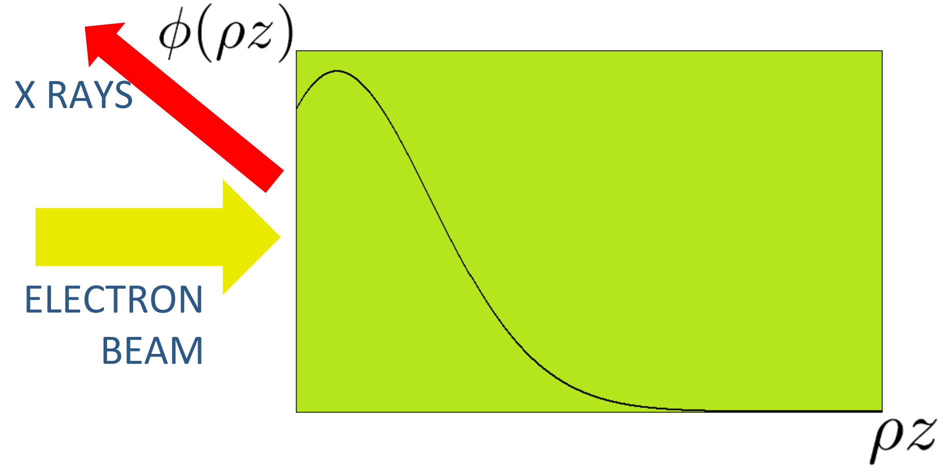
$$\frac{I_{film}}{I_{ref,film}} = f(\tau)$$ COATING METHOD

$$\frac{I_{sub}}{I_{ref,sub}} = g(\tau)$$ SUBSTRATE METHOD

- Simple experimental equipment
- Direct non-destructive measurement
- High spatial resolution
- Applicability range

EDS for areal density evaluation

Probability Function
for X-Ray Production
(PFXP)



MODIFIED SURFACE GAUSSIAN MODEL (electron diffusion)

$$\phi(\sigma) = \gamma \exp\left[-\alpha^2 \sigma^2\right]\left[1 - \frac{\gamma - \phi(0)}{\gamma} e^{(-\beta\sigma)}\right]$$

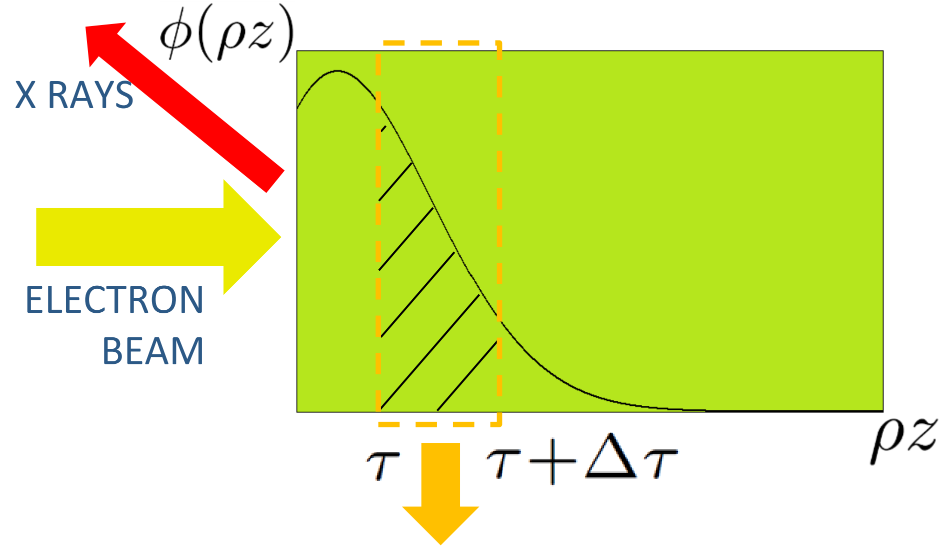
Isotropical propagation
of electrons

Directional propagation
near the surface

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

EDS for areal density evaluation

X-rays producion
in a sample layer



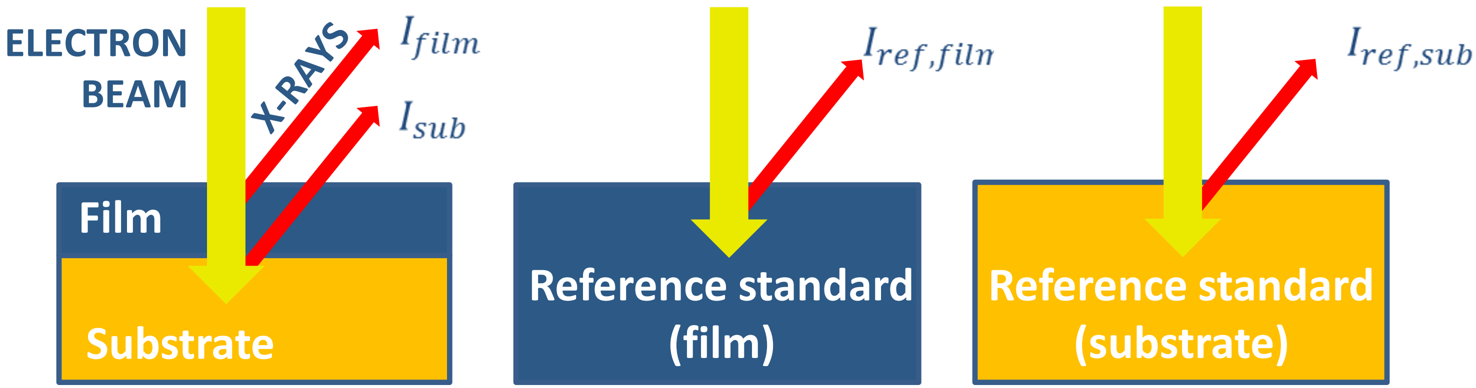
$$I_1 = k \int_{\Delta\tau} C_1 \phi_1(\sigma) \exp(-\chi\sigma) d(\sigma)$$

X-Ray
Production

X-Ray
Attenuation

G. H. Cockett *et al.,* Brit. J. Appl. Phys., 14, 813 (1963)

EDS for areal density evaluation



COATING METHOD

$$\frac{I_{\mathrm{C,i}}}{I_{\mathrm{C,i}}^{\mathrm{ref}}} = \frac{\int_0^{\tau} C_{\mathrm{i}} \phi_{\mathrm{C,i}}(\sigma) \exp\left(-\chi_{\mathrm{C}} \sigma\right) \mathrm{d}\sigma}{\int_0^{\infty} C_{\mathrm{i}}^{\mathrm{ref}} \phi_{\mathrm{C,i}}^{\mathrm{ref}}(\sigma) \exp\left(-\chi_C^{\mathrm{ref}} \sigma\right) \mathrm{d}\sigma}$$

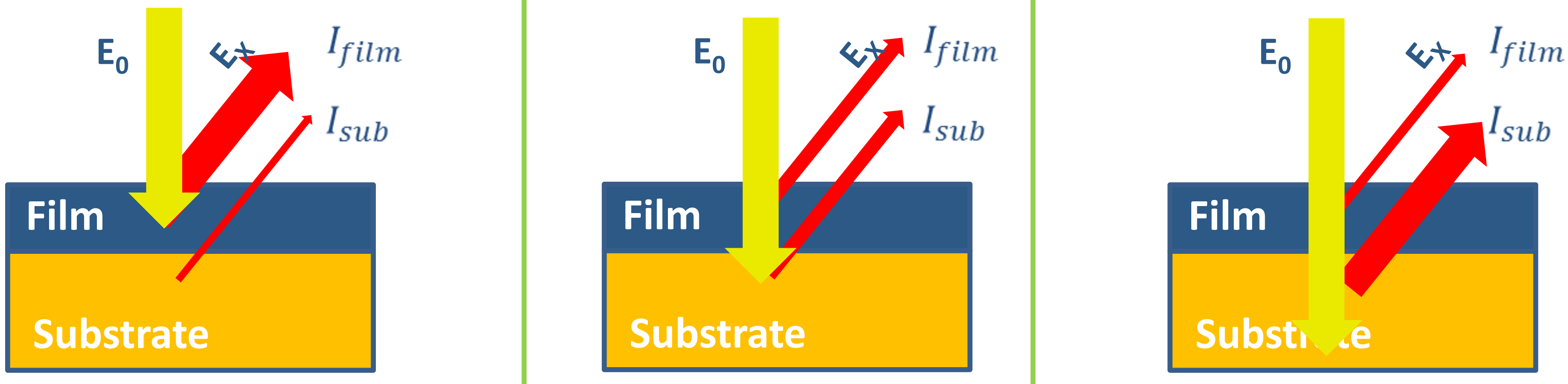
SUBSTRATE METHOD

$$\frac{I_{\mathrm{S,j}}}{I_{\mathrm{S,j}}^{\mathrm{ref}}} = \exp^{(-\chi_{\mathrm{C}} \tau)} \frac{\int_{\tau}^{+\infty} C_{\mathrm{j}} \phi_{\mathrm{S,j}}(\sigma) \exp\left[-\chi_{\mathrm{S}}(\sigma - \tau)\right] \mathrm{d}\sigma}{\int_0^{+\infty} C_{\mathrm{j}}^{\mathrm{ref}} \phi_{\mathrm{S,j}}^{\mathrm{ref}}(\sigma) \exp\left(-\chi_{\mathrm{S}}^{\mathrm{ref}} \sigma\right) \mathrm{d}\sigma}$$

Experimental issues

Electron penetration

- **Both layers** must be probed



$$\frac{I_{film}}{I_{ref,film}} \approx 1 \qquad \frac{I_{film}}{I_{ref,film}} = f(\rho z) \qquad \frac{I_{film}}{I_{ref,film}} \approx 0$$

$$\frac{I_{sub}}{I_{ref,sub}} \approx 0 \qquad \frac{I_{sub}}{I_{ref,sub}} = g(\rho z) \qquad \frac{I_{sub}}{I_{ref,sub}} \approx 1$$

ELECTRON ENERGY

SELECTION OF ACCELERATION VOLTAGE

Target manufacturing

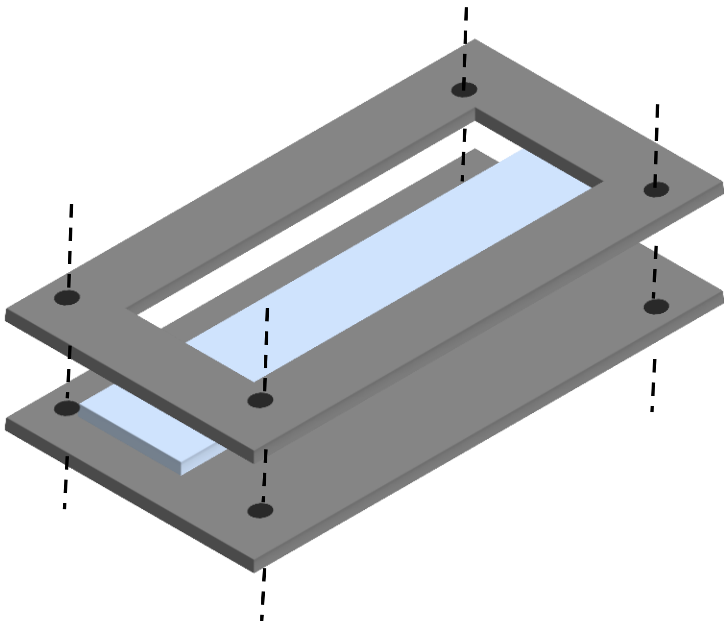
Target holders required to handle thin Al substrates (0.75-12 μm)

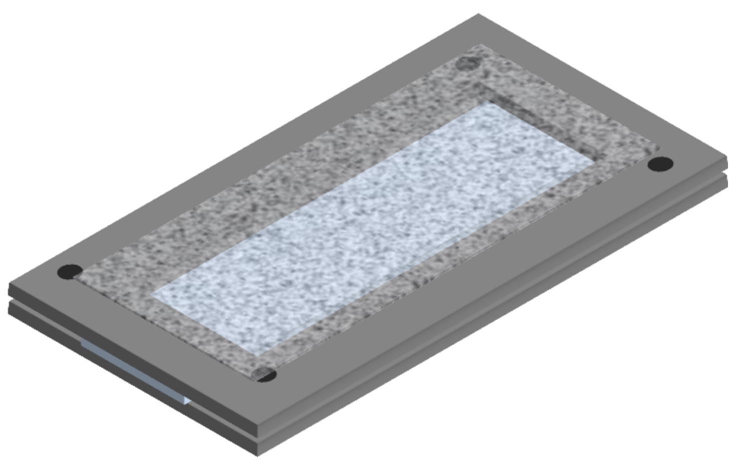
IN ALL THE EXPERIMENT PHASES

- foam deposition
- target transport
- target irradiation

TAILORED FOR SPECIFIC FACILITY

- UHI100 LIDyL
- PULSER I GIST





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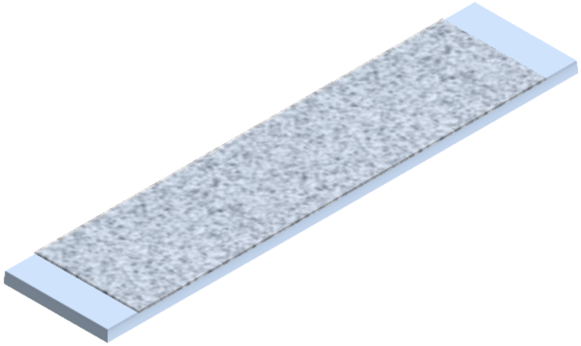

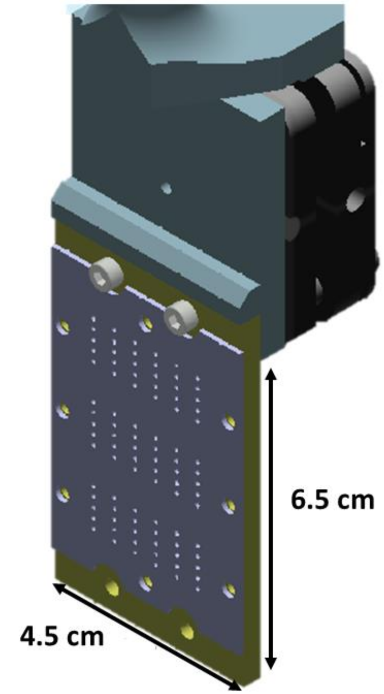

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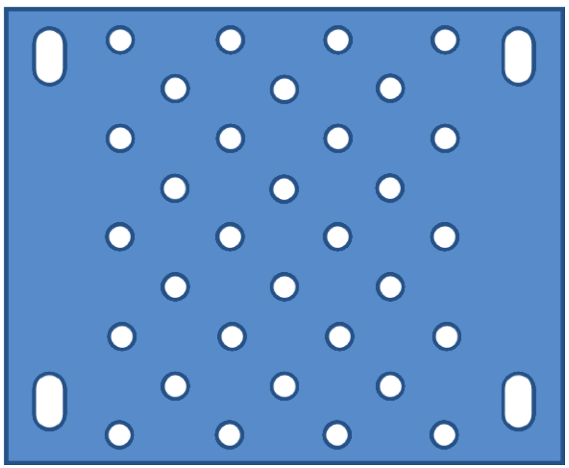

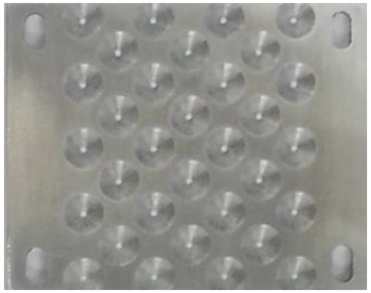

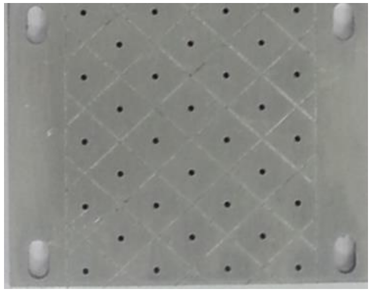

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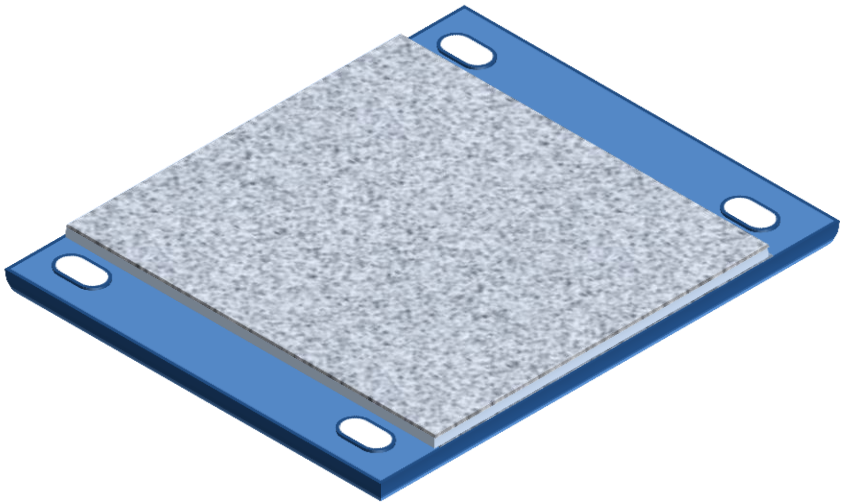

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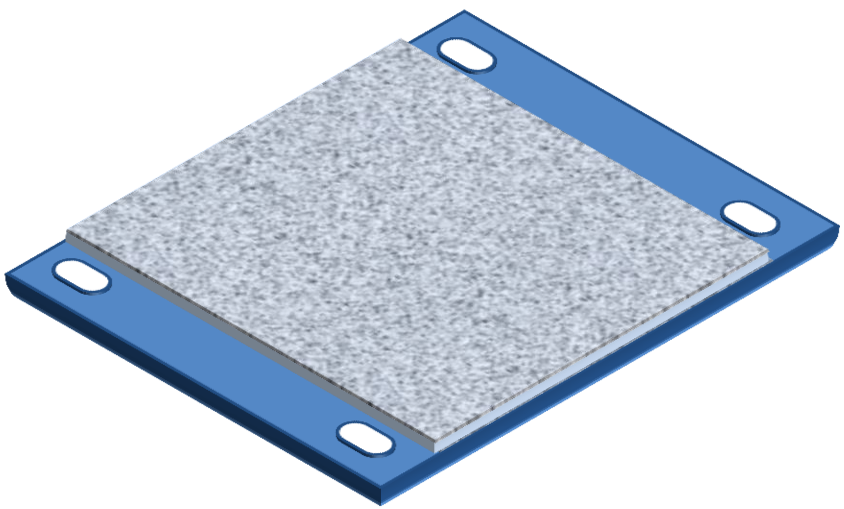

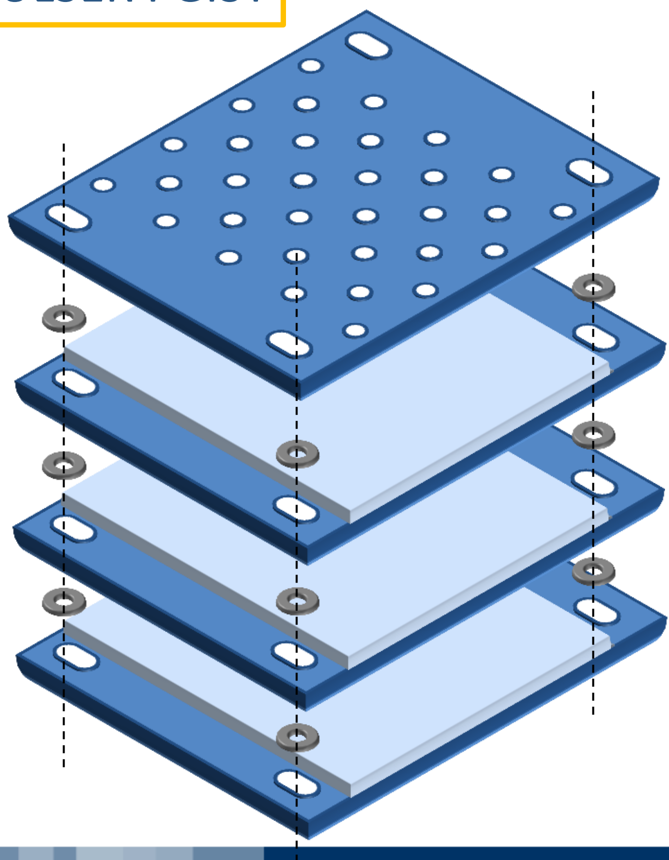

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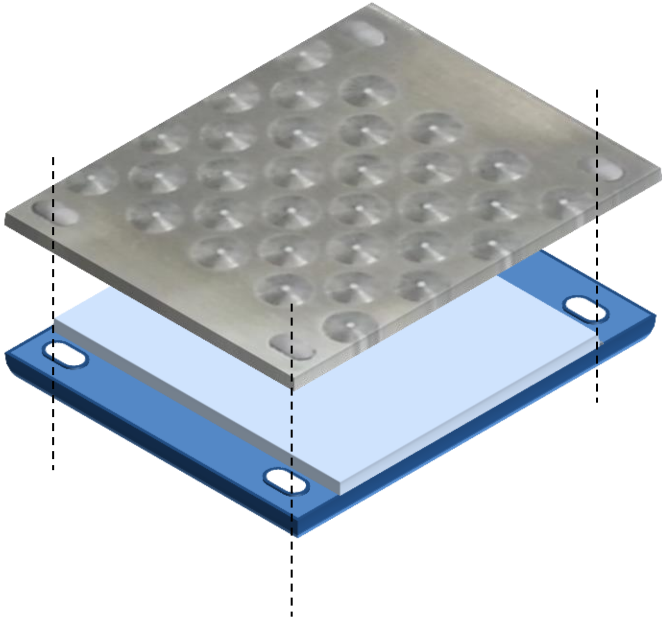

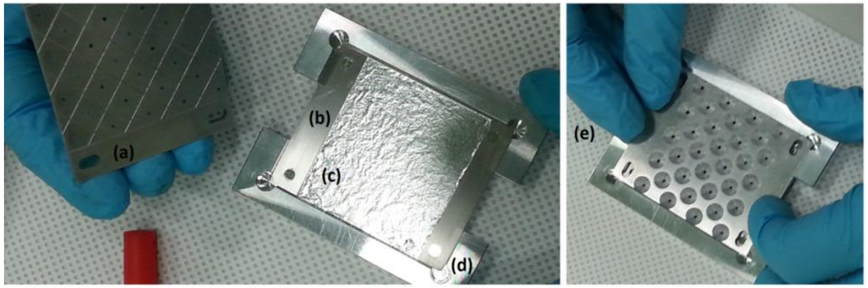

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Acceleration experiment @ UHI100 LIDyL

GOAL proof of concept experiment on foam-attached targets @ moderate intensity

STRATEGY intensity scan ($I_L < 5x10^{19}$ W/cm^2) for

- foam-attached targets
- bare Al targets

Experimental setting

LASER PULSE

τ_L = 25 fs

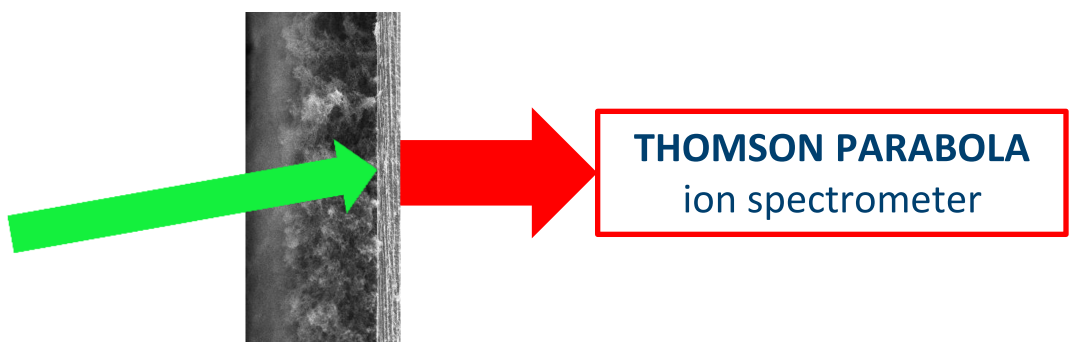
E_L= 2 J

λ = 0.79 μm

Contrast 10^7 and 10^{12}

w_0 = 3.5 - 150 μm

α=10°



FOAM-ATTACHED TARGET

LC: Al 10 μm + **C foam** 23 μm, 6.8 mg/cm^3

HC: Al 1.5 μm + **C foam** 12 μm, 6.8 mg/cm^3

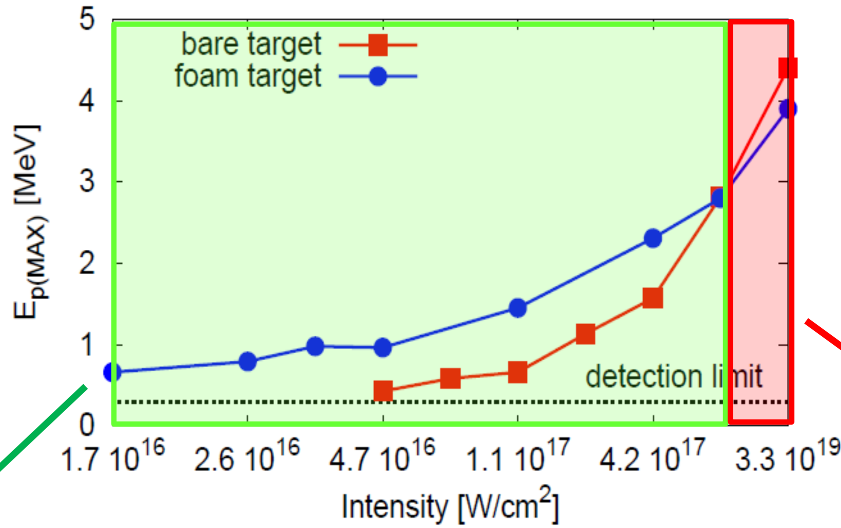
Acceleration experiment @ UHI100 LIDyL

NanoLab

in collaboration with: cea SACLAY

Laser parameters:

τ_L = 25 fs
E_L=2 J, contrast 10^{12}
w_0 = 3.5-150 μm
λ=0.79 μm
α=10°
I~10^{16} -10^{19} W/cm^2



Target:

Al 1.5 μm + **C foam** 12 μm
n_{foam}=6.8 mg/cm^3 = 1.2 n_{cr}

I<10^{18} W/cm^2

Non relativistic: p generation quenched in bare Al
Partial ionization (C^{2+}/C^{4+}): under-critical plasma

Enhanced proton acceleration regime

I~10^{19} W/cm^2

Full ionization: over-critical plasma
Non-optimized foams

Ordinary proton acceleration regime

M. Passoni *et al.*, Plasma Phys. Control. Fusion, **56** 045001 (2014)

Acceleration experiment @ UHI100 LIDyL

NanoLab

in collaboration with: CEA Saclay

Laser parameters:

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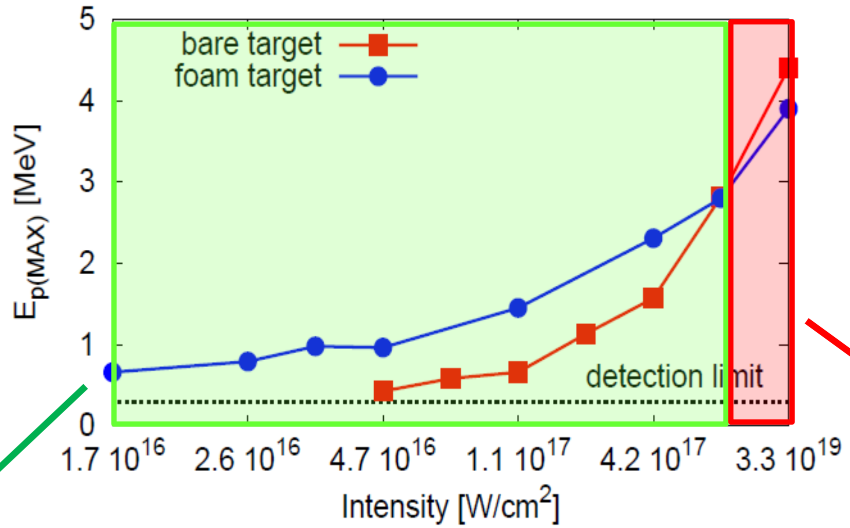
α=10°
I~10^{16} -10^{19} W/cm²



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Partial ionization (C^{2+}/C^{4+}): under-critical plasma

Enhanced proton acceleration regime

I~10^{19} W/cm²

Full ionization: over-critical plasma
Non-optimized foams

Ordinary proton acceleration regime

1) **Proof-of-principle** of enhanced TNSA
2) TNSA-like **MeV protons** accessible **with just 10^{16}–10^{17}** W/cm² !!!
3) **Optimization** required

M. Passoni *et al.*, Plasma Phys. Control. Fusion, **56** 045001 (2014)

Acceleration experiment @ PULSER I - GIST

NanoLab

GOALS

extensive study of the effects of:

- target properties
- laser intensity and polarization

STRATEGY

intensity scan ($I_L > 5\times10^{19}$ W/cm^2) for:

- bare Al and foam-based targets with different properties
- circular, s- and p-polarization

Experimental setup

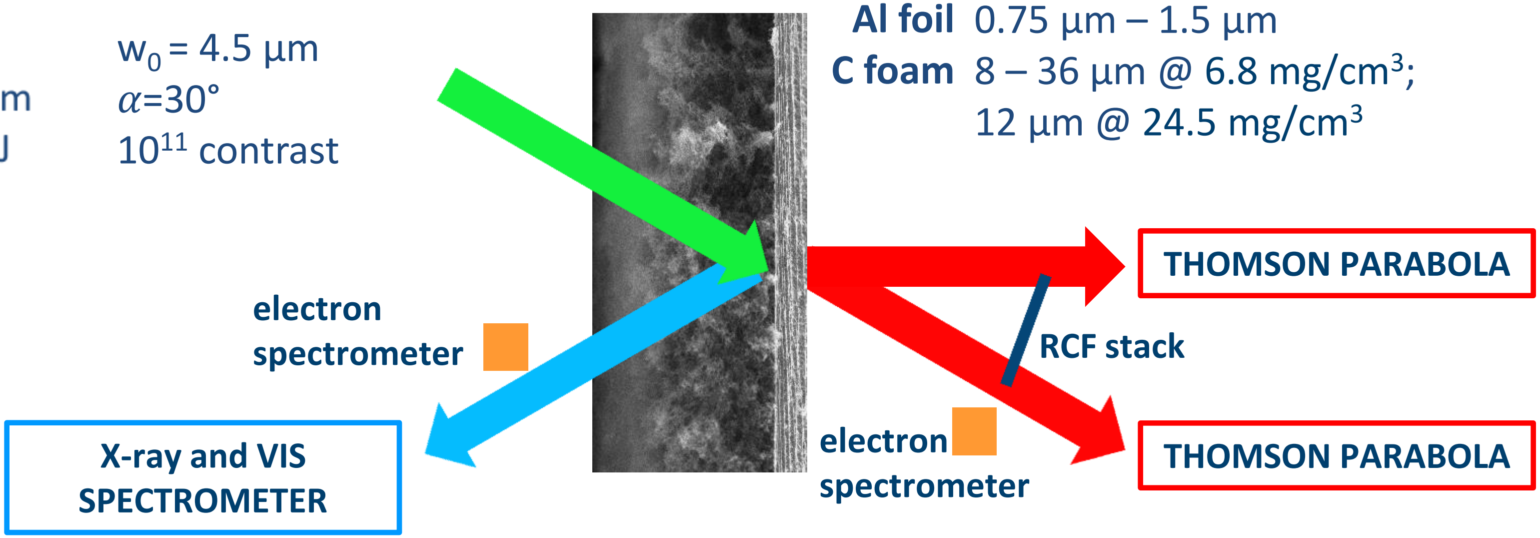
LASER PULSE

τ_L = 29 fs
λ = 0.79 µm
E_L = 1 – 8 J

w_0 = 4.5 µm
α=30°
10^{11} contrast

FOAM-BASED TARGETS

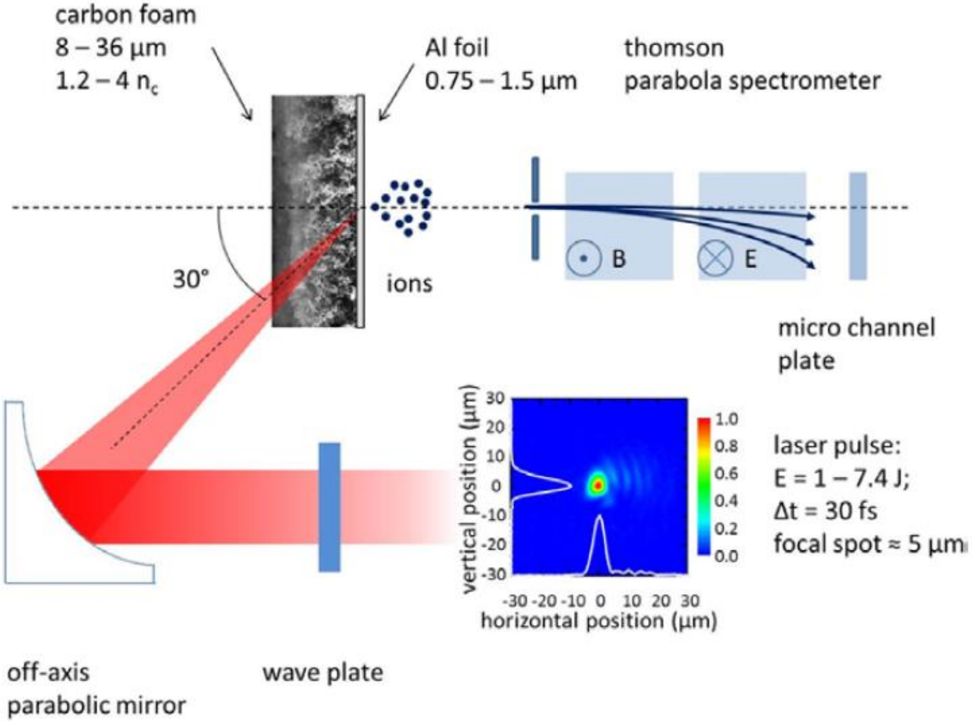
Al foil 0.75 µm – 1.5 µm
C foam 8 – 36 µm @ 6.8 mg/cm^3;
12 µm @ 24.5 mg/cm^3

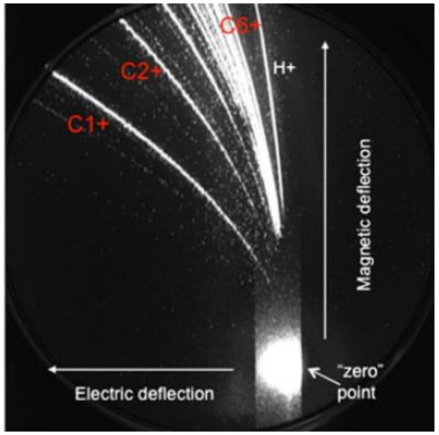


Acceleration experiment @ PULSER I - GIST

Experimental setup @ GIST

intensity scan ($I_L > 5x10^{19}$ W/cm^2) for
- bare Al and foam-based targets with different properties
- circular, s- and p-polarization

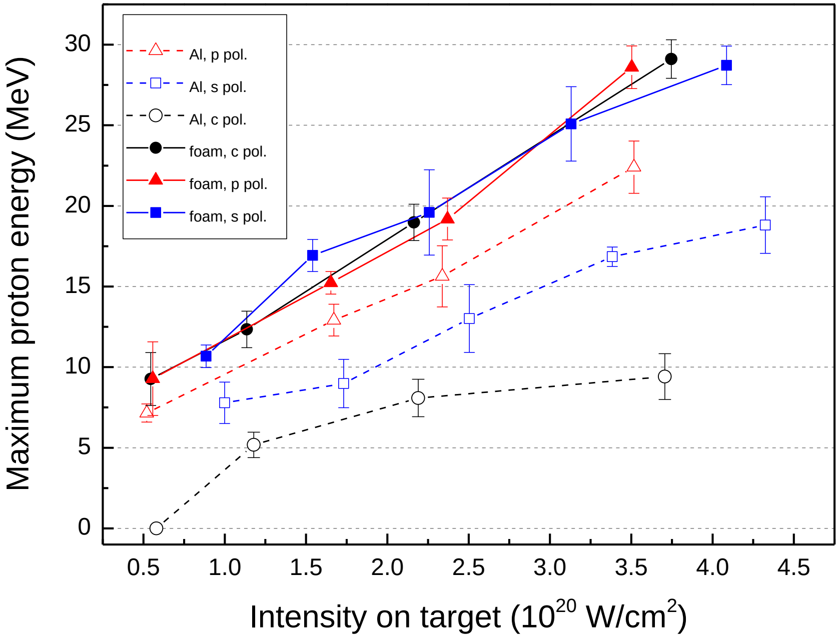




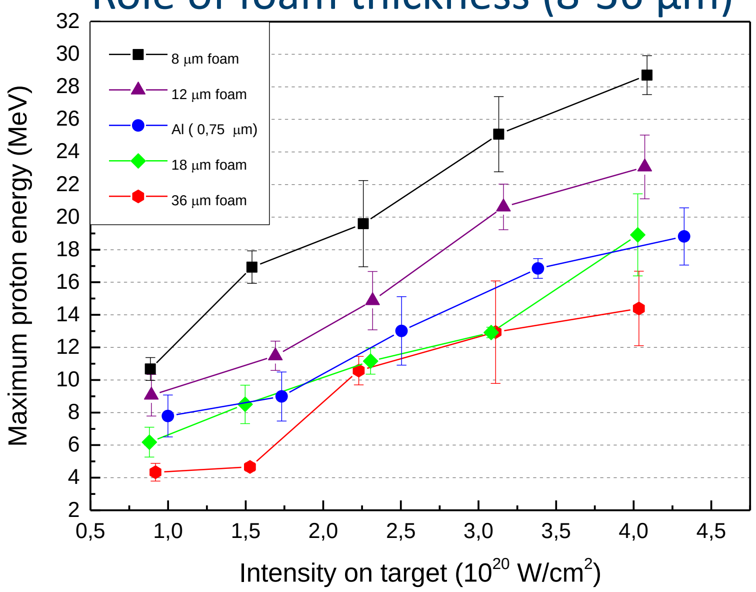
Acceleration experiment @ PULSER I GIST

Role of pulse properties Al (0.75 μm) + foam (6.8 mg/cm³, 8 μm)

- pulse **intensity**
- pulse **polarization**: s, p and circular polarization



Role of foam thickness (8-36 μm)



Dependence on **polarization**

- strong for Al foils
- reduced for foam targets

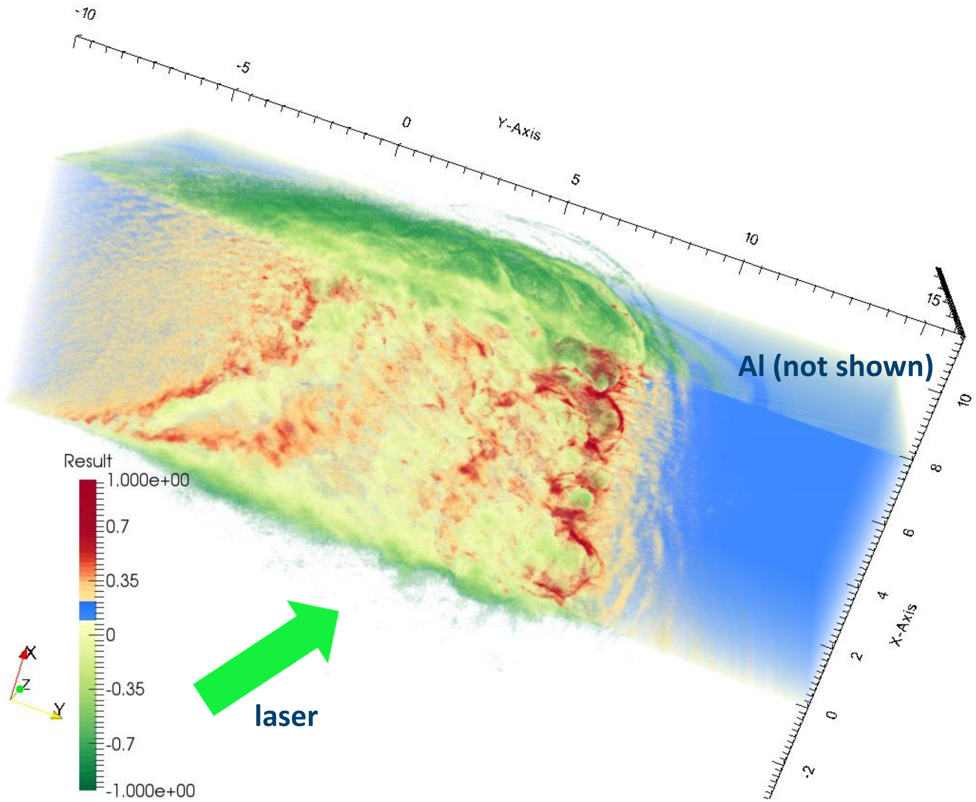
- foam: **volume interaction** vs Al: surface interaction
- irregular foam surface: polarization **definition**?
- role of target **nanostructure**?

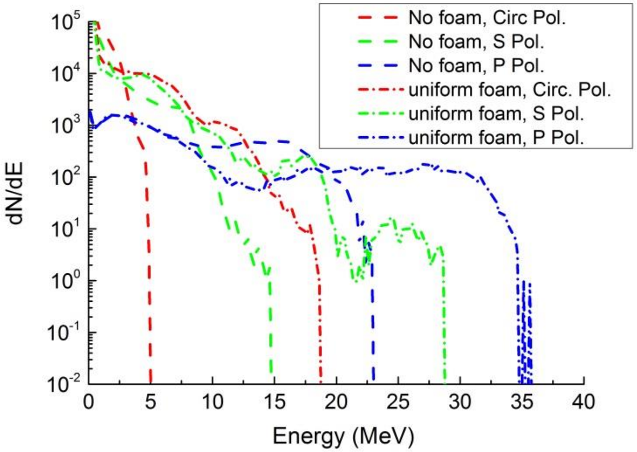
M. Passoni *et al.*, Plasma Phys. Control. Fusion, **56** 045001 (2014)

3D PIC with uniform foam

Simplified approach: uniform near-critical density layer

- Laser pulse: $a_0 = 18$ (= 7×10^{20} Wcm^{-2}), $w_0 = 4$ μm, $\tau_L = 33$ fs, $\alpha = 30°$
- Al layer: thickness = 0,5 μm, $n = 40\ n_c$
- Foam layer: thickness = 8 μm, $n = 1\ n_c$





- agreement for Al (c, s, p)
- E_{max} enhancement with foam
- significant dependence on polarization even with foam

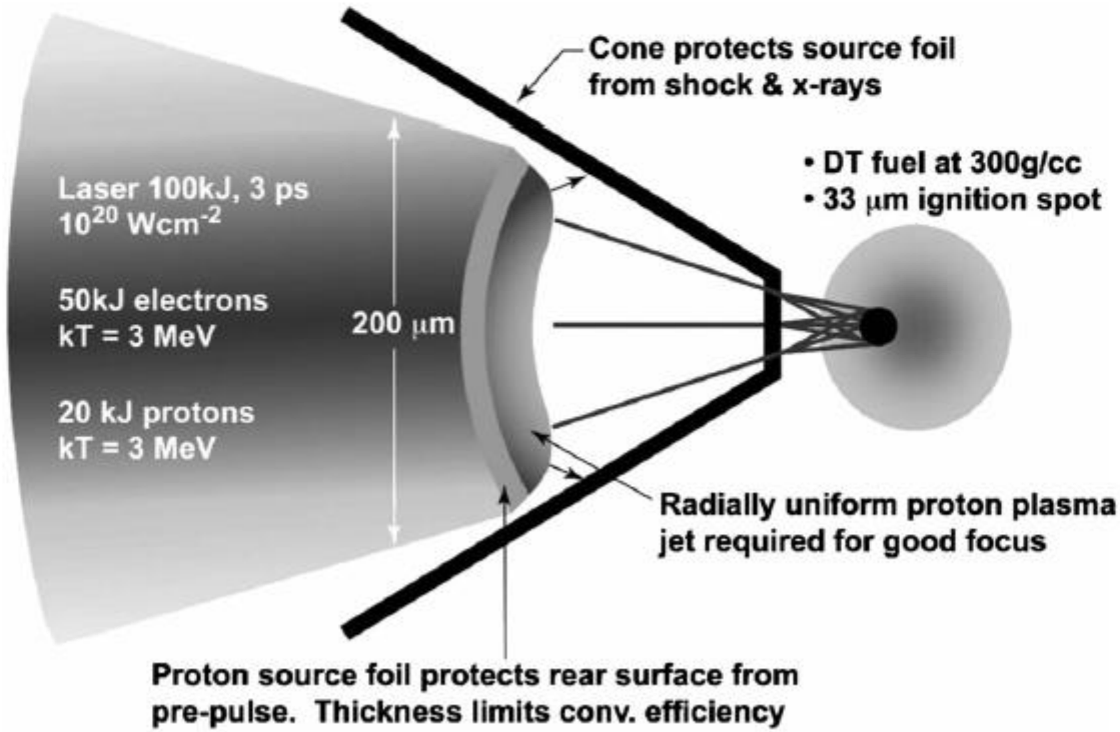
more realistic foam model, including nanostructure, to describe such details

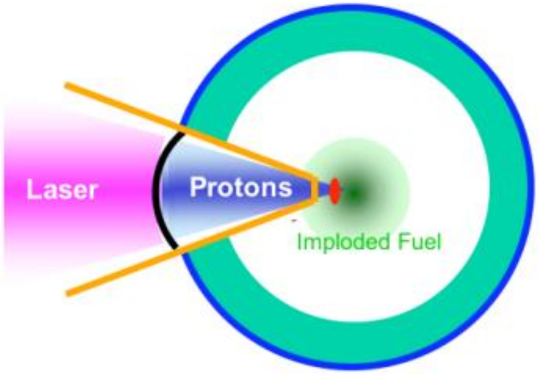
Summary

- performance enhancement for optimized foam properties
- max proton energy ≈ 30 MeV with 30fs, 8J, $4x10^{20}$ W/cm^2 pulses & multi-μm targets. Strong increase in mean ion energy, as well. Further optimization expected.
- low sensitivity to Al thickness, pulse polarization and contrast
- target concept compatible with high repetition rate experiments (?)
- ...exploration of these & other concepts, with focus on possible applications in material/nuclear science/engineering in the

  "**ENSURE**" project (ERC Co Grant 2014, 5 years from Sept. 1st 2015)

Proton-based fast ignition



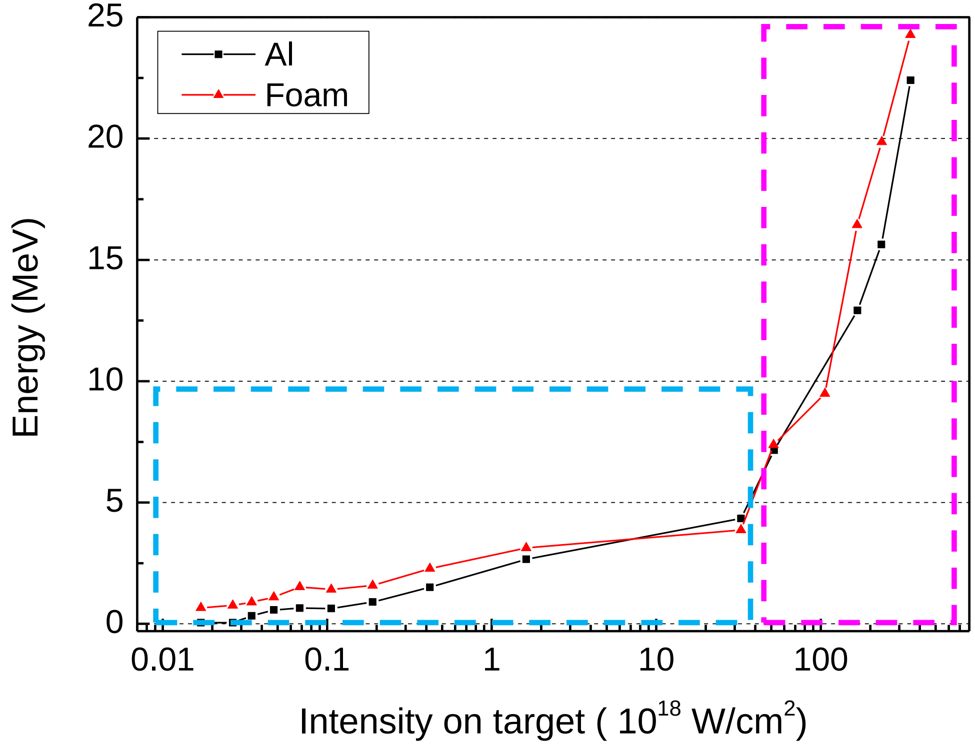


Key, M. H., 2007, Phys. Plasmas 14, 055502.

Conclusions…

Laser driven ion acceleration experiments

- several intensity decades explored
- different experimental conditions



PULSER I GIST

- Incidence angle 30°
- Pulse energy variation
- Al 0.75 μm

UHI100 LIDyL

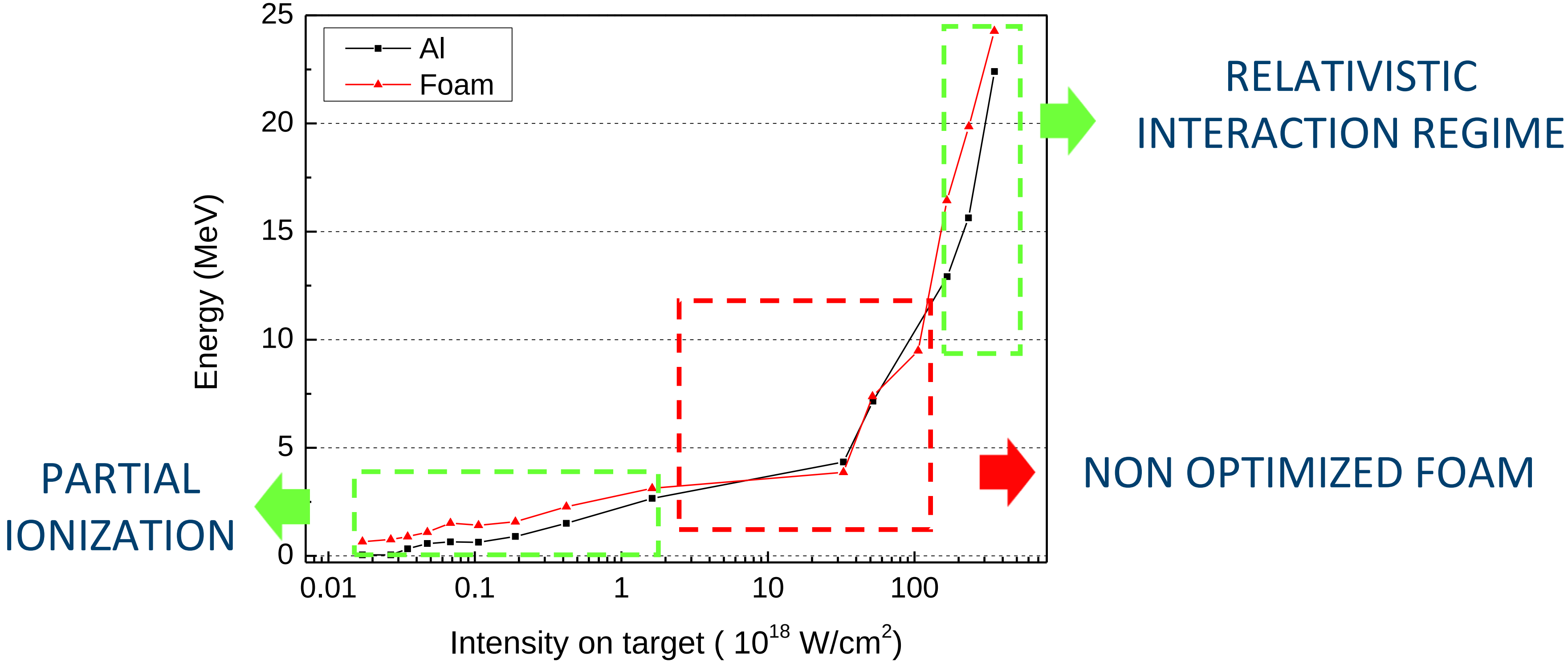
- Incidence angle 10°
- Focal spot variation
- Al 1.5 μm

p-pol; foam: 1.2 n_c, 12 μm

Conclusions…

Laser driven ion acceleration experiments

- several intensity decades explored
- 3 interaction regimes



p-pol; foam: 1.2 n_c, 12 μm