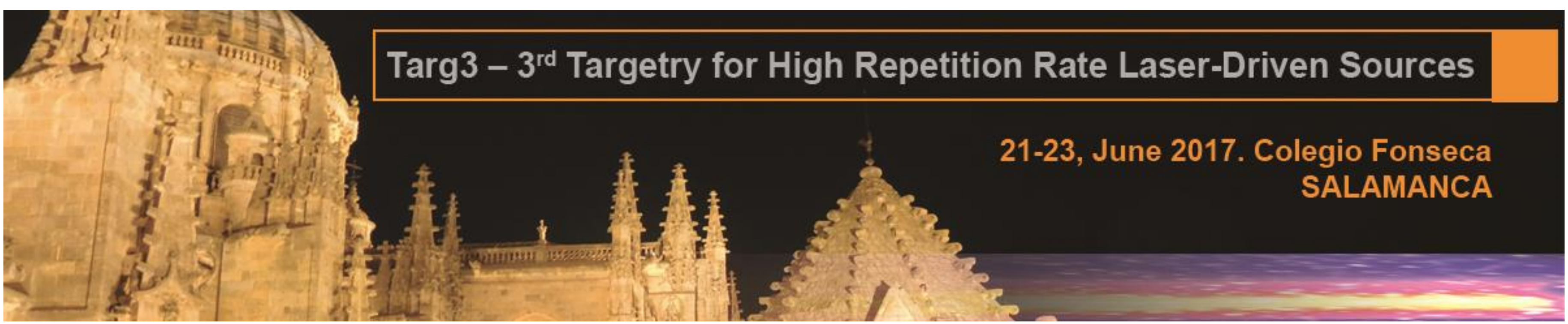
POLITECNICO MILANO 1863

Near critical density, foam-based, multi-layered targets for laser-driven ion acceleration

David Dellasega

Salamanca, 23/06/2017



The ENSURE group at Politecnico di Milano

Matteo Passoni

Associate professor

ERC-2014-CoG No.647554

ENSURE

Ongoing collaborations with:

HZDR

OSAKA UNIVERSITY

SourceLAB

ERC-PoC: **INTER**

Queen's University Belfast

The ENSURE project

Laser-driven ion acceleration
Theoretical/numerical & experimental investigation

Materials science
Development of low-density foams & advanced targets for laser-plasma experiments

Applications in materials and nuclear science
Materials characterization (e.g. PIXE) with laser-driven ions
Secondary neutron sources for radiography and detection[...]

Fundamental physics and laboratory astrophysics
Laser interaction with (near-critical) nanostructured plasmas
Collisionless shock acceleration of ions

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Margherita Zavelani-Rossi
Associate professor

Valeria Russo
Researcher

4 Post-docs

D. Dellasega

A. Maffini

L. Fedeli

L. Cialfi

2 PhD students

A. Formenti

A. Pazzaglia

3 Master's students

F. Mirani

A. Tentori

M. Sala

People involved in experimental activities

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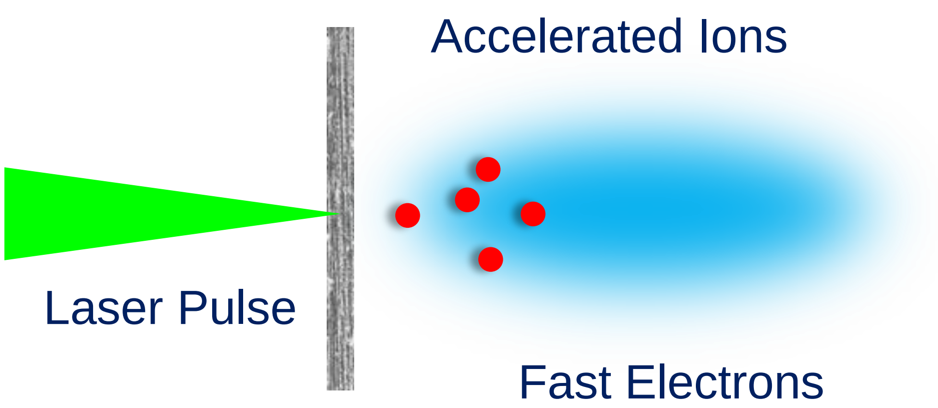
Enhanced Target Normal Sheath Acceleration

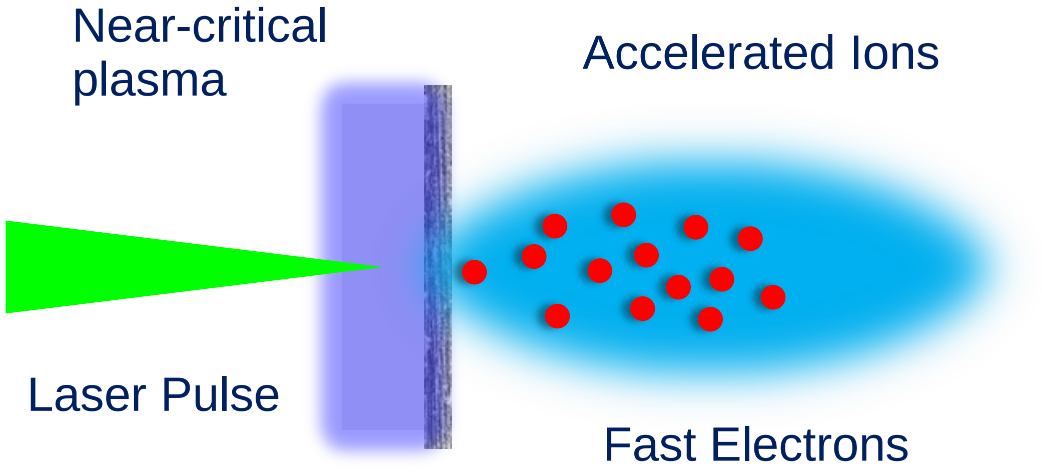
Conventional Target



Solid Foil
Surface interaction mechanisms

Target Normal Sheath Acceleration (TNSA)

Multi-layer near critical Target



Solid Foil + Low Density Layer
Volume & Surface Interaction Mechanisms

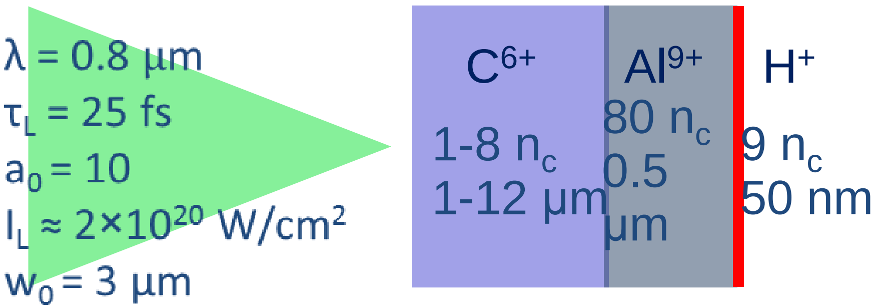
Enhanced TNSA

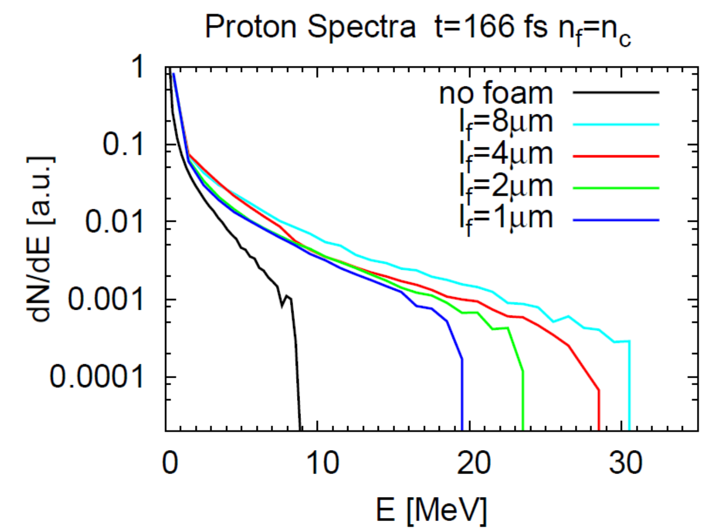
- Higher laser energy absorption
- Enhanced fast electron production
- Enhanced number and maximum energy
- of accelerated ions

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

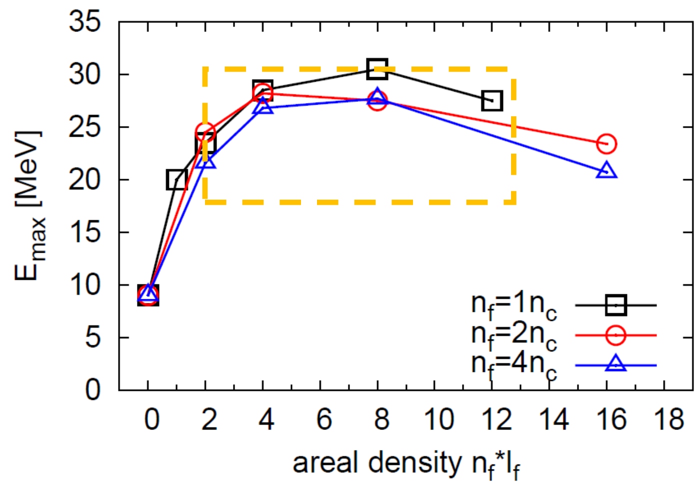
Foam-attached targets for Enhanced-TNSA

2D PIC simulations (ALaDyn code)





Enhanced Maximum Proton Energy
For foam attached Targets



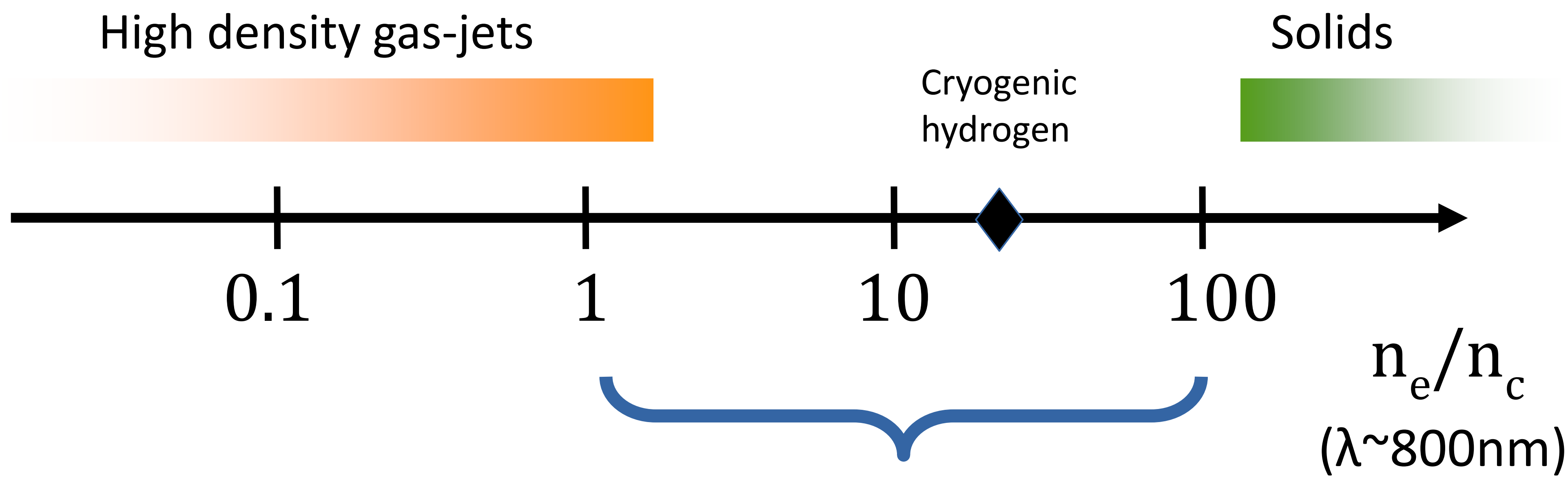
density < 10 mg/cm³ (for λ≈1 μm)

thickness from 5 to 10s μm

optimal areal density range
for given laser parameters

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

...from near critical plasma to low density materials



Few options:

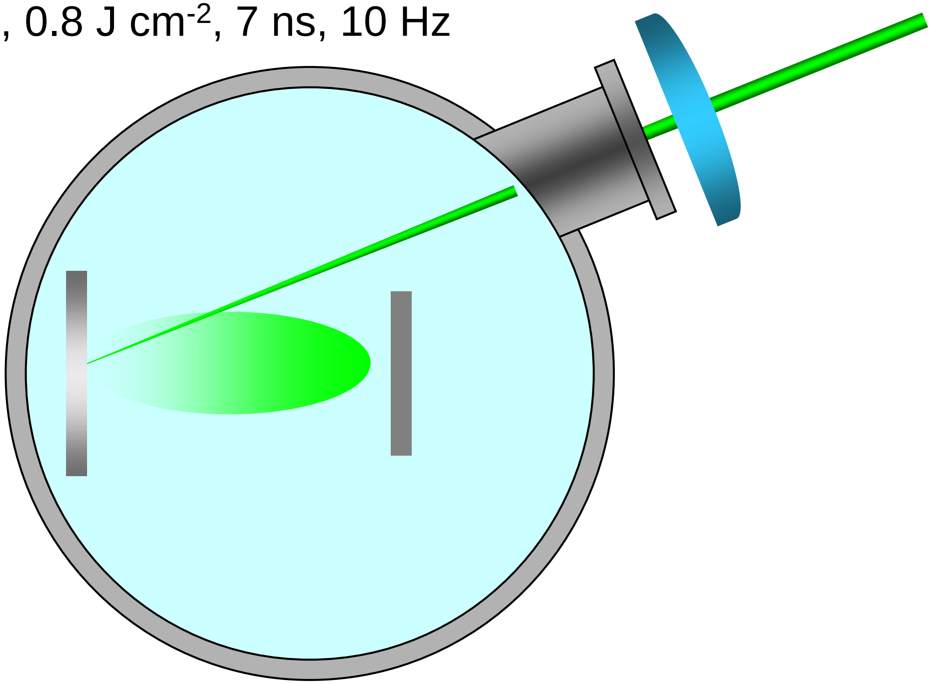
- Pre-heating
- **Very low-density nanostructured materials with 1/500th density of solids**
  - Aerogels[1]
  - Nanotube arrays[2]
  - Foams[3]

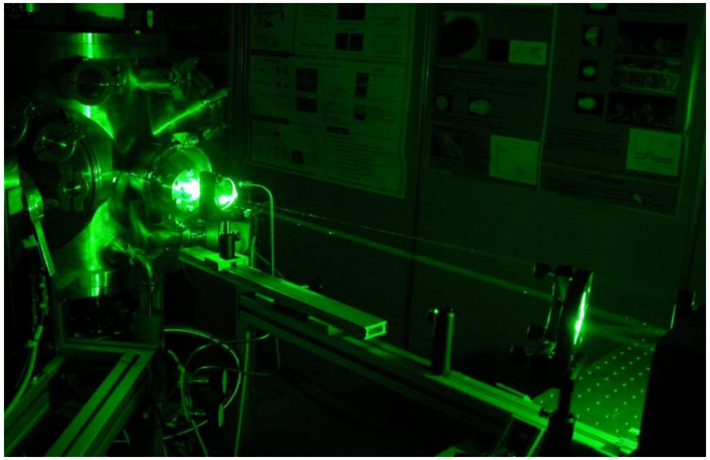
[1]Willingale et al. PRL 96 (2006)
[2]Bin et al. PRL 115 (2015)
[3]Zani et al. Carbon 56 (2013)

ns Pulsed Laser Deposition (PLD) in a background gas

Nd:YAG laser

532 nm, 0.8 J cm^{-2}, 7 ns, 10 Hz





Substrate

Thickness down to 10s nm

Diameter up to 5 cm

Rotation few rpm (film thickness profile)

PLD Target

e.g. pyrolytic graphite

Background gas

(film structure)

Ar-He, pressure up to 1000 Pa

Target-substrate distance

(film structure)

45-85 mm

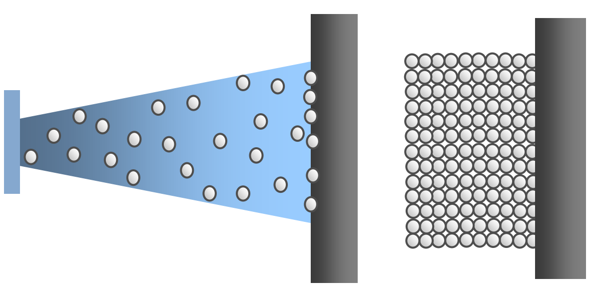
Process duration

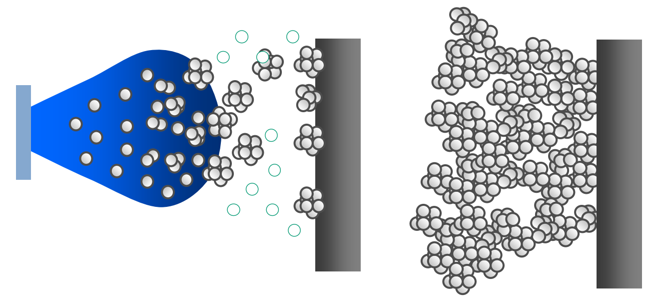
(film thickness)

5 – 60 min

A. Bailini *et al.*, Appl. Surf. Sci., **253** 8130 (2007); A. Zani *et al.*, Carbon, **56** 358 (2013)

ns Pulsed Laser Deposition (PLD) in a background gas





High kinetic energy

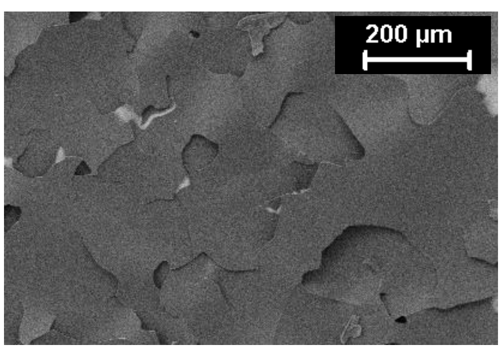
Atom-by-atom deposition

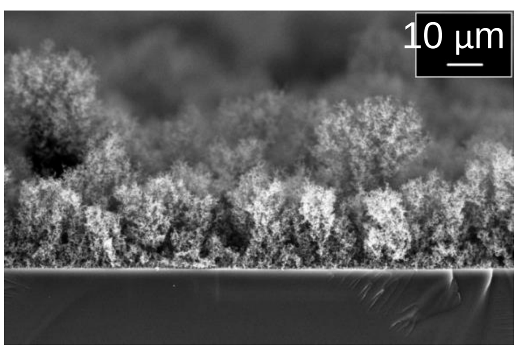
Process parameters

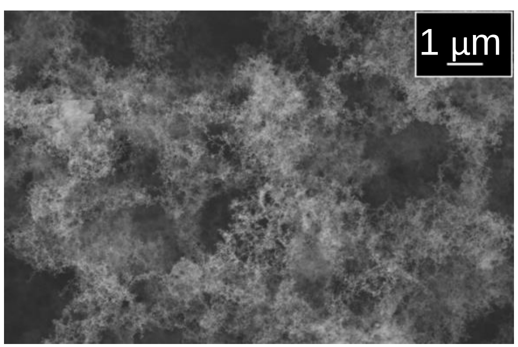
(e.g. gas pressure)

Low kinetic energy

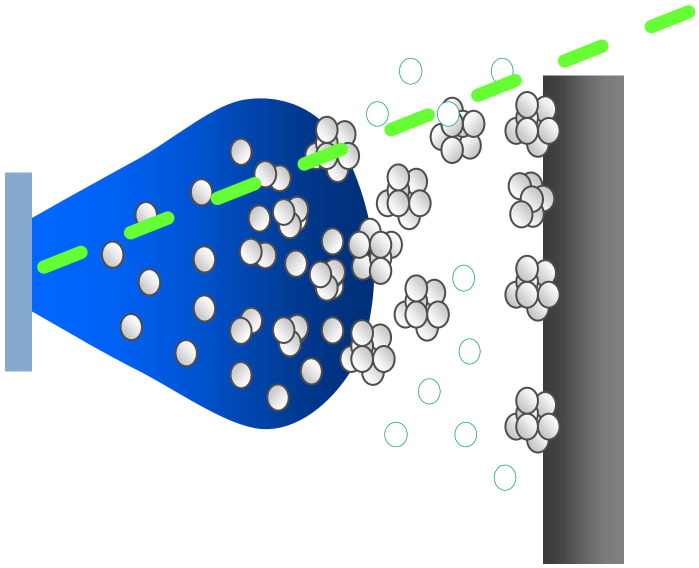
Cluster formation







Nanoparticle formation by ns PLD in background gas

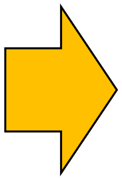


1. Adiabatic expansion
2. Shock wave formation
3. Nanoparticle synthesis
4. Nanostructured film formation

Not possible use a unique model for describing the whole process

Investigating the role of

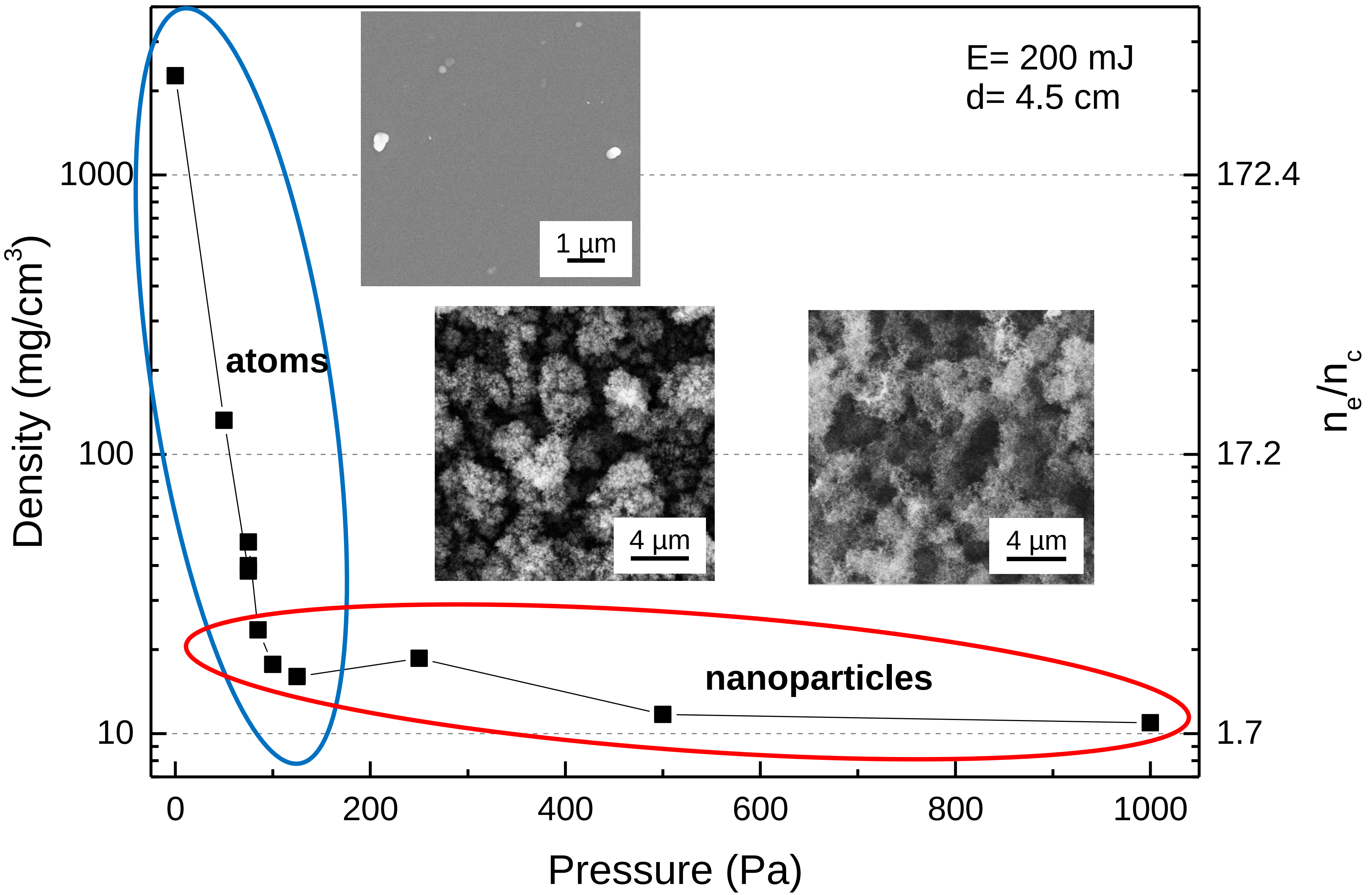
- Pulse energy
- Ar pressure
- Target-substrate distance



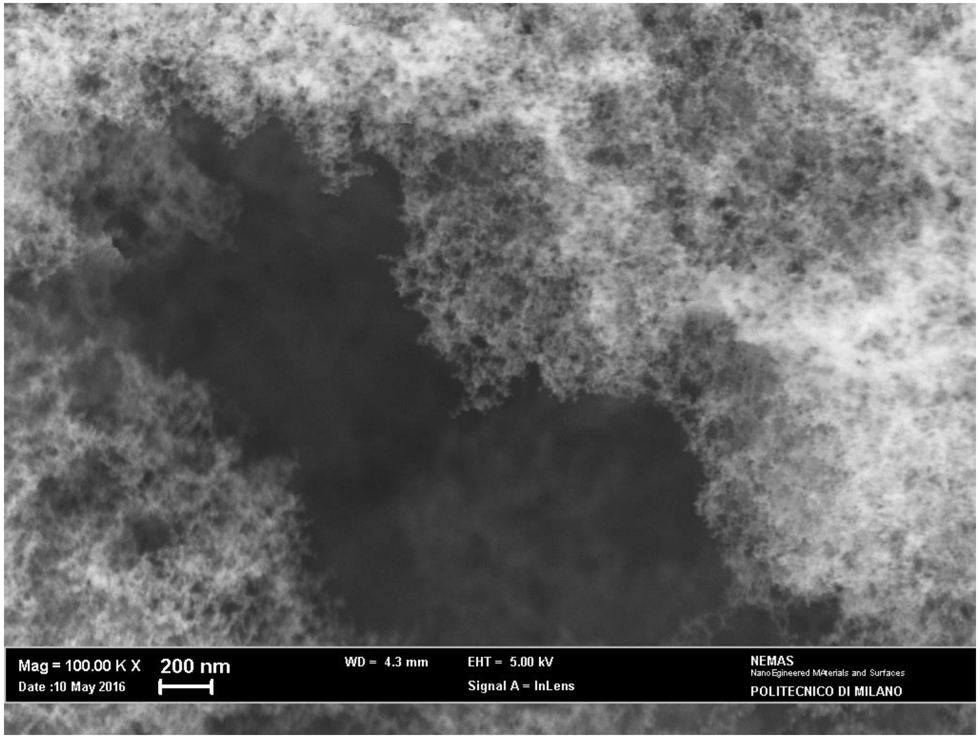
To control

- energy of the species,
- deposition rate,
- coupling with expanding plasma
- expansion dynamics,
- diam. of nanoparticles,
- porosity of the film

Role of process parameters - pressure

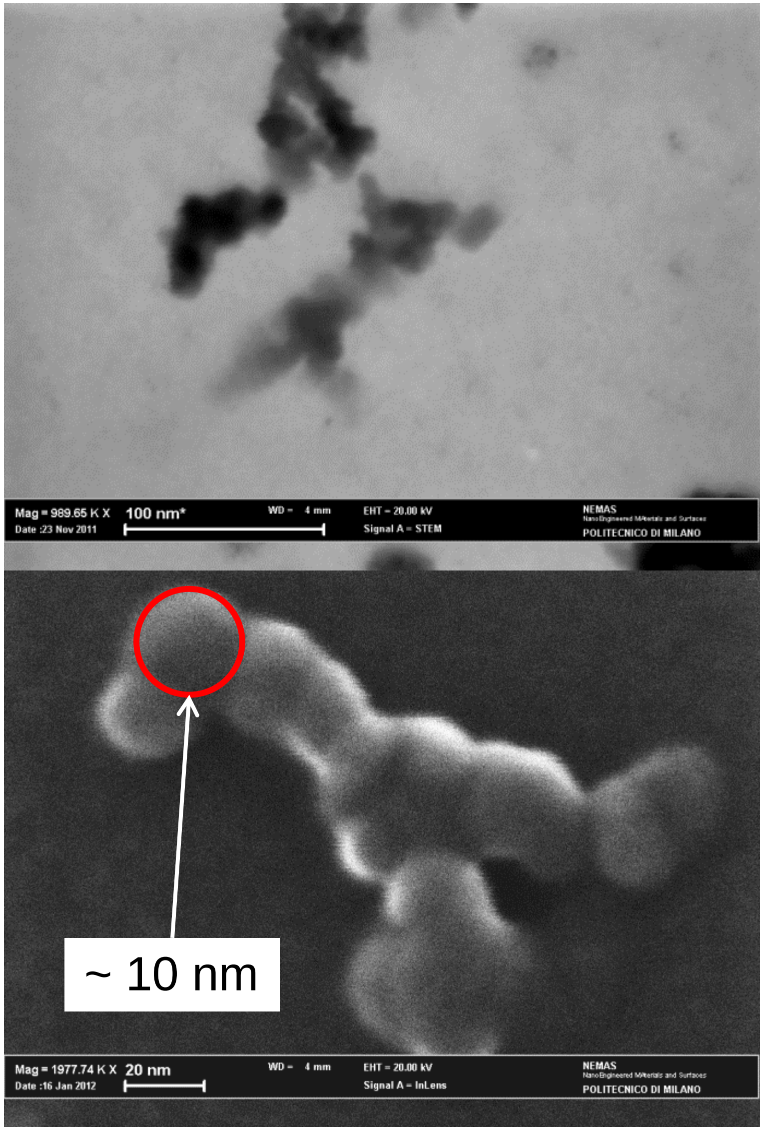


Relatively easy to produce Carbon nanoparticles

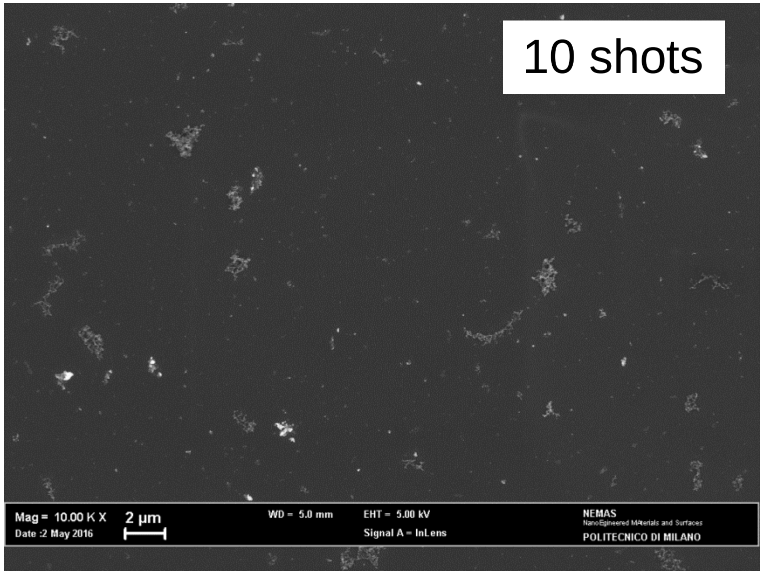


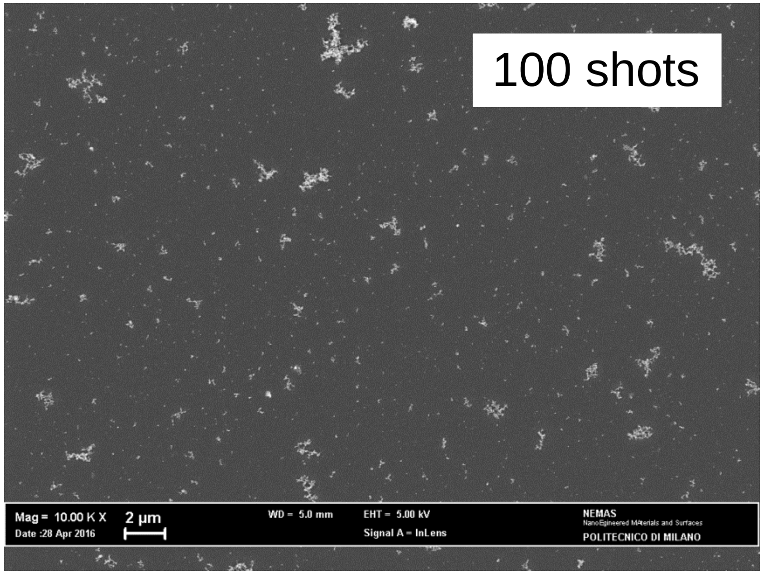
Foam: PLD parameters

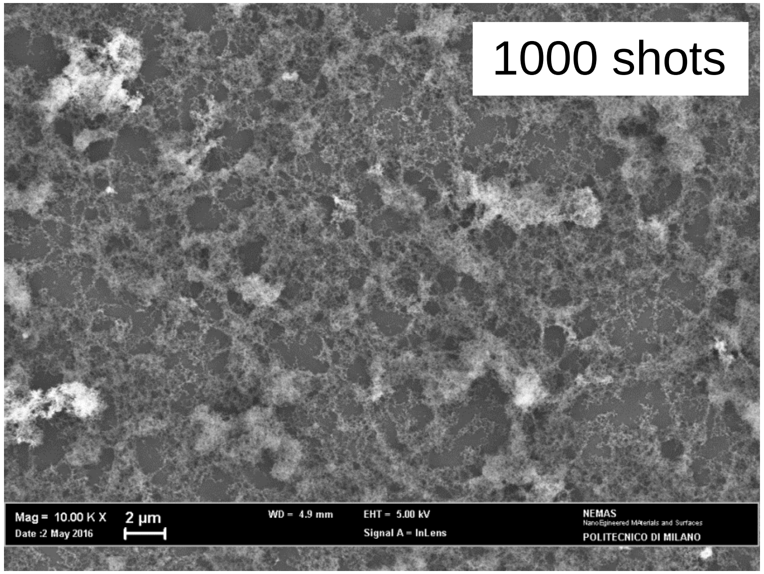
- E=100 mJ
- P=100 Pa Ar
- d_{ts}=8.5 cm
- thickness = 12 µm

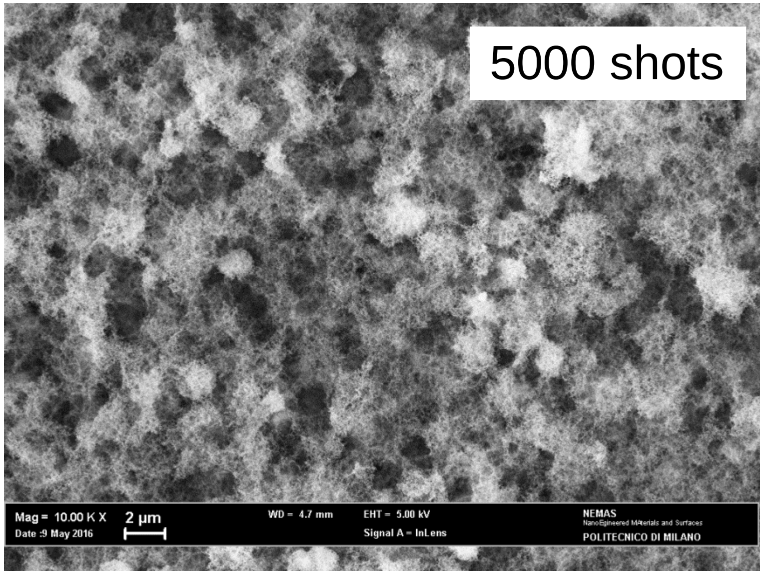


Not so easy to control the growth of the whole film!









It is difficult to obtain thin and homogeneous/reliable coatings!

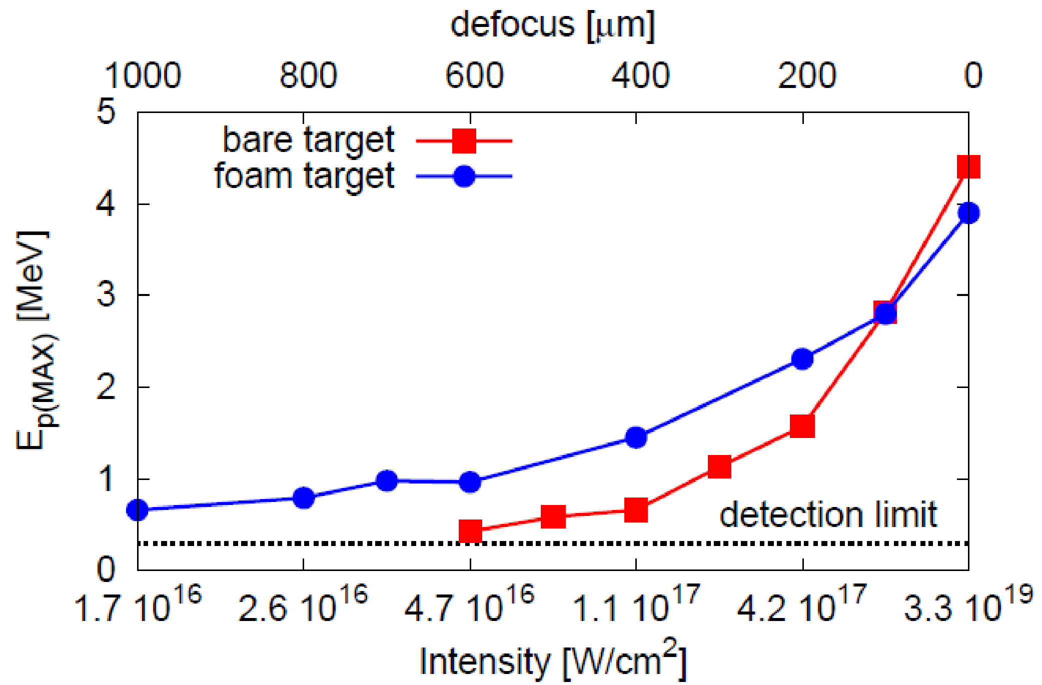
Acceleration experiment @ UHI100 LIDyL

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

in collaboration with:
P. Martin, T. Ceccotti et al.

Foam: PLD parameters

- E=100 mJ
- P=100 Pa Ar
- d_{ts}=8.5 cm
- thickness = 12 µm
- Substrate = Al 1.5 µm



Ion acceleration: laser parameters

- Energy on target = 1 J
- Intensity = 1.7 10^{16} - 3.3 10^{19} W/cm^2
- Angle of incidence = 10°

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

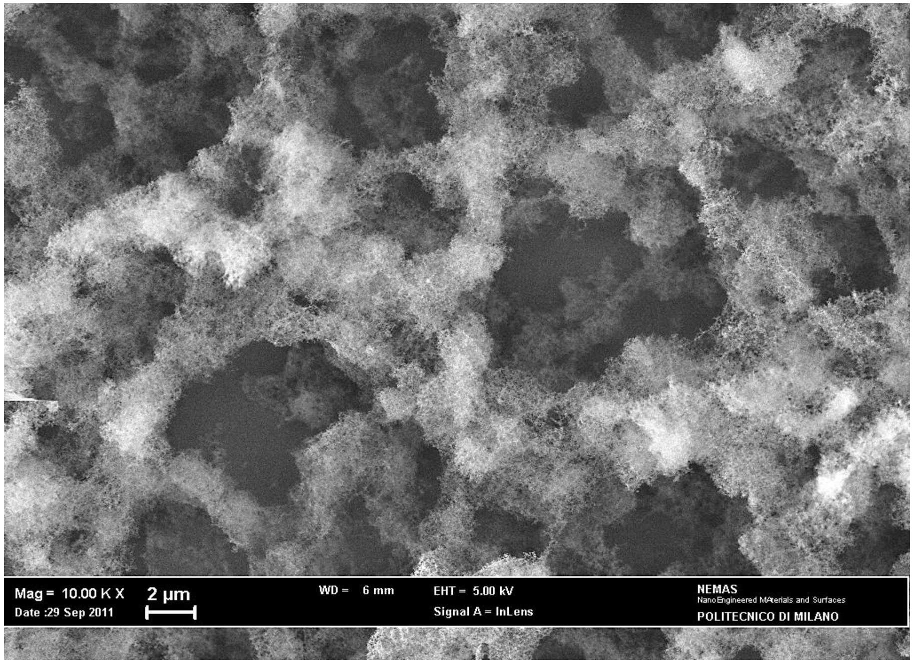
Partial foam ionization (C^{2+}/C^{4+}):
under-critical plasma

- Enhanced proton acceleration regime
- Foams are too thick

Improving uniformity at lower thickness

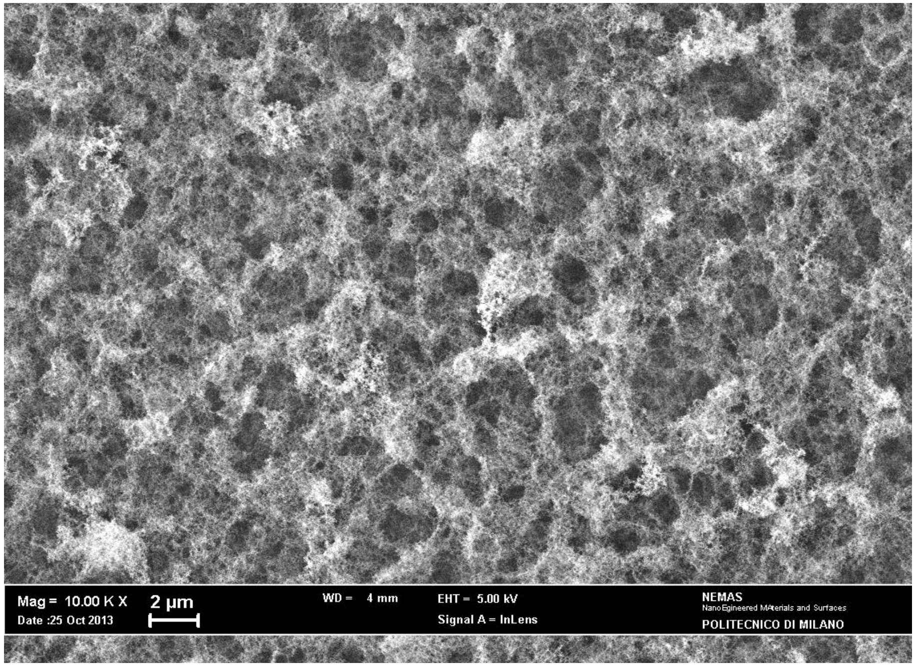
Foam: PLD parameters

- E=100 mJ
- P=100 Pa Ar
- d_{ts}=8.5 cm
- thickness = 8 µm



Foam: PLD parameters

- E=130 mJ
- P=500 Pa Ar
- d_{ts}=4.5 cm
- thickness = 8 µm



Improved reproducibility + lower thickness available

Acceleration experiment @ Pulser GIST

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

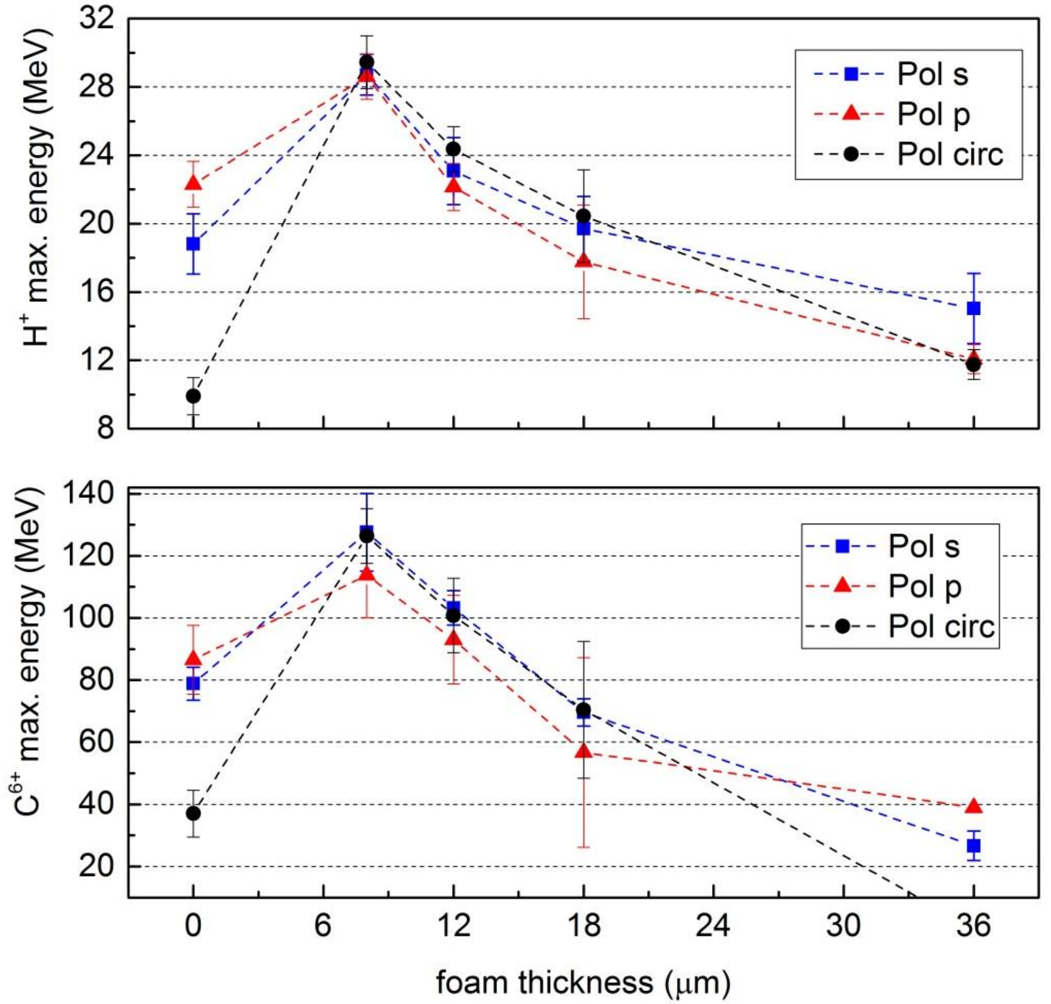
in collaboration with:
I. W. Choi, C. H. Nam et al.

Foam: PLD parameters

- E=130 mJ
- P=500 Pa Ar
- d_{ts}=4.5 cm
- thickness = 8, 12, 18, 36 μm
- Substrate = Al 0.75 μm

Ion acceleration: laser parameters

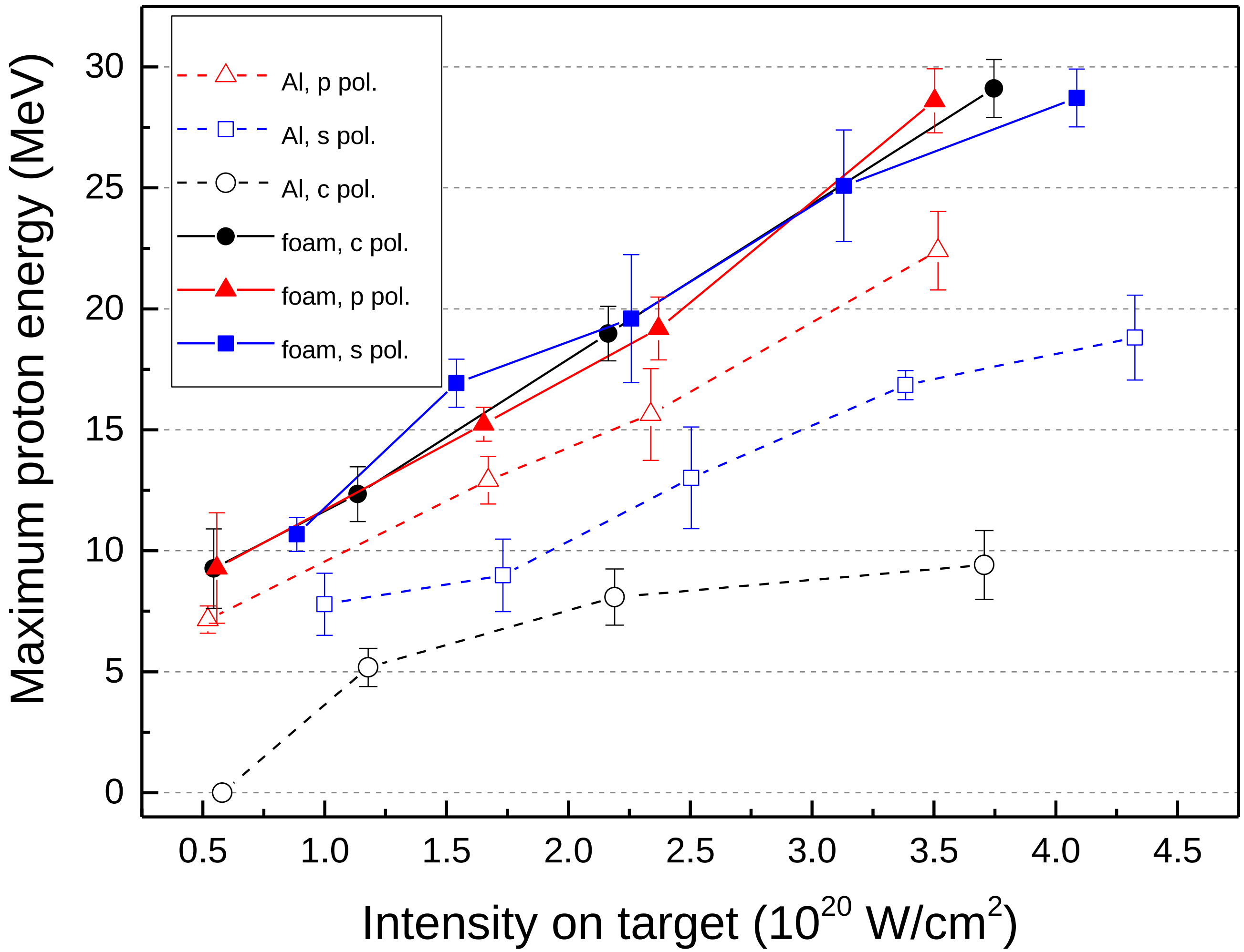
- Energy on target = 8 J
- Intensity = 0.5 10^{20} - 5 10^{20} W/cm^2
- Angle of incidence = 30°



Higher ion energies using thinner foams

Acceleration experiment @ Pulser GIST

in collaboration with:
I. W. Choi, C. H. Nam et al.

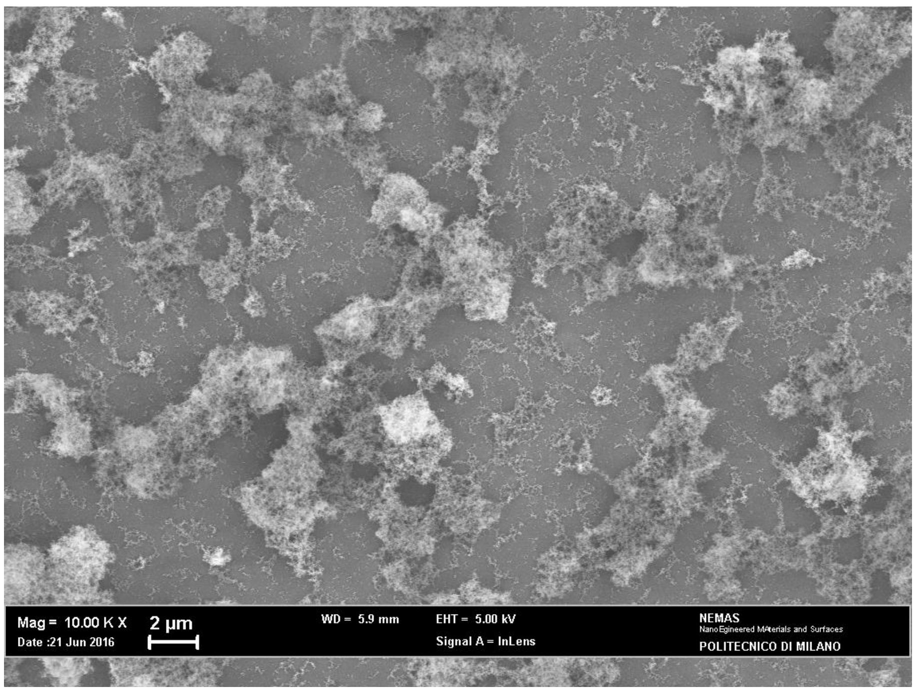


Insensible respect to polarization (volume interaction)

Further improvement: foam thickness below 5 µm

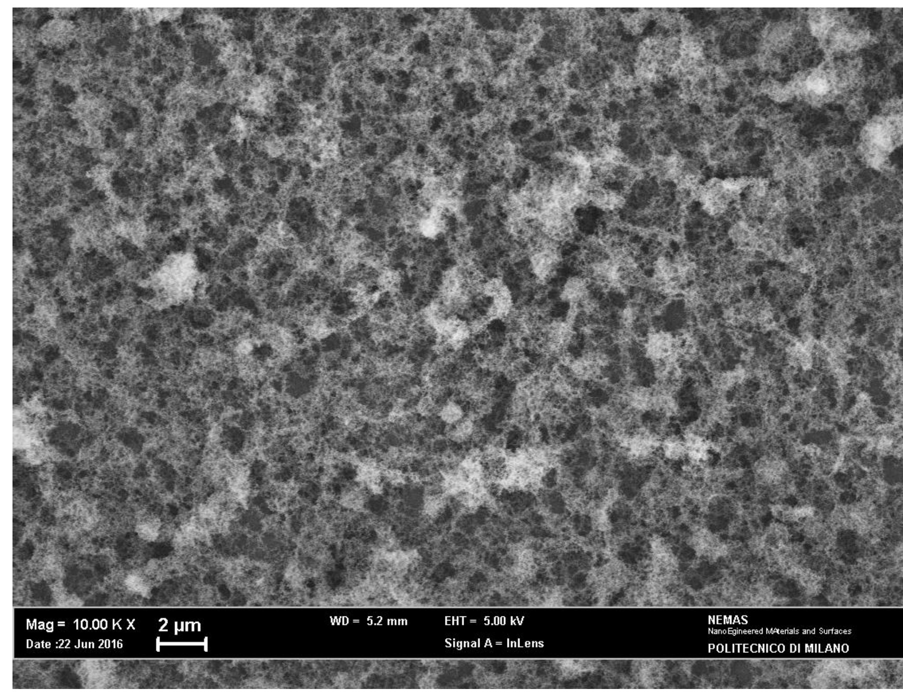
Foam: PLD parameters

- E=130 mJ
- P=500 Pa Ar
- d_{ts}=4.5 cm
- thickness = 4 µm



Foam: PLD parameters

- E=200 mJ
- P=1000 Pa Ar
- d_{ts}=4.5 cm
- thickness = 4 µm



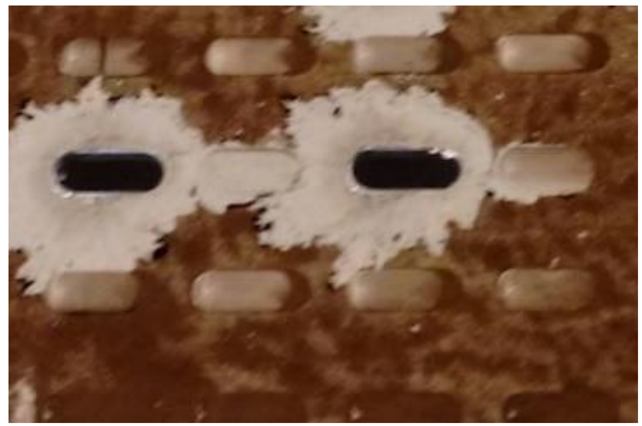
Increasing the energy of the impinging nanoparticles

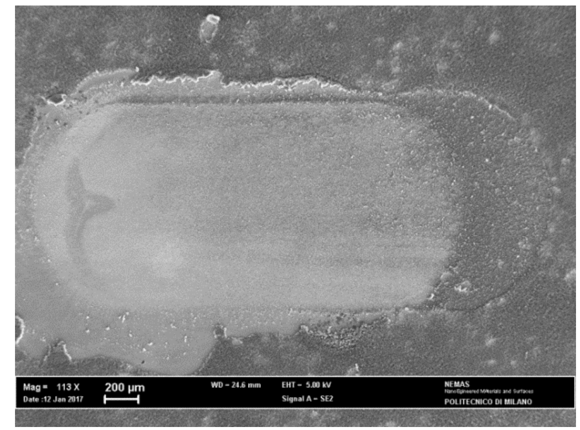
Target development for experiments @ DRACO

Thin foam issues

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

Usual target holder
120 available shots

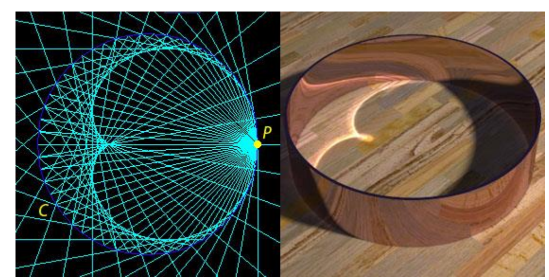




Damage in neighbouring targets

Careful engineering of target holder

- Ceramic
- 23 available shots x holder
- Rectangular holes



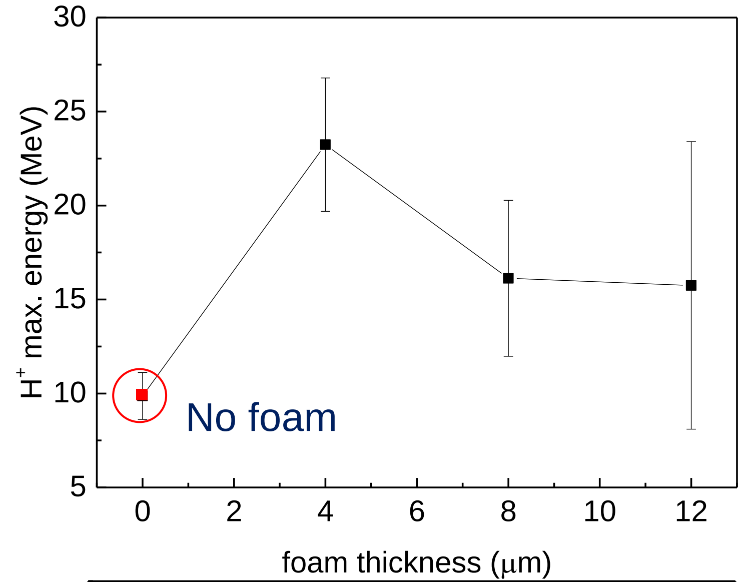
Caustics formation due to the shape of the hole

Acceleration experiments @ DRACO 150 TW (preliminary data)

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

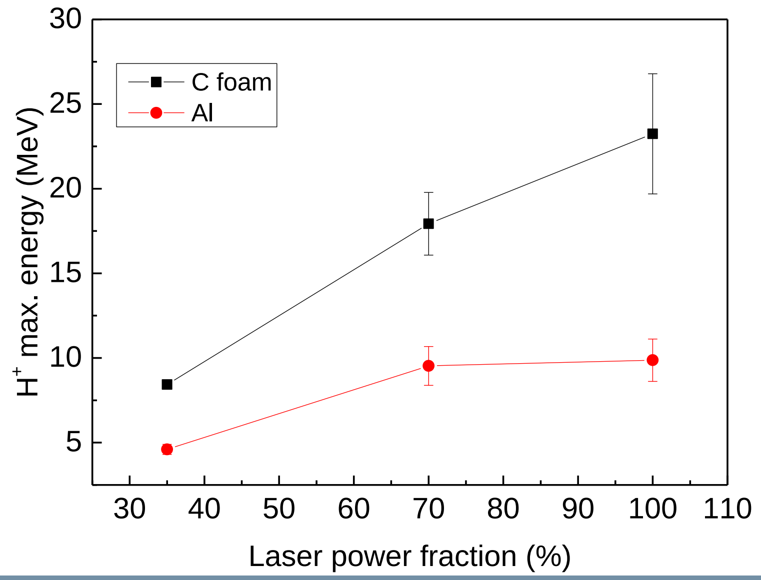
Foam: PLD parameters

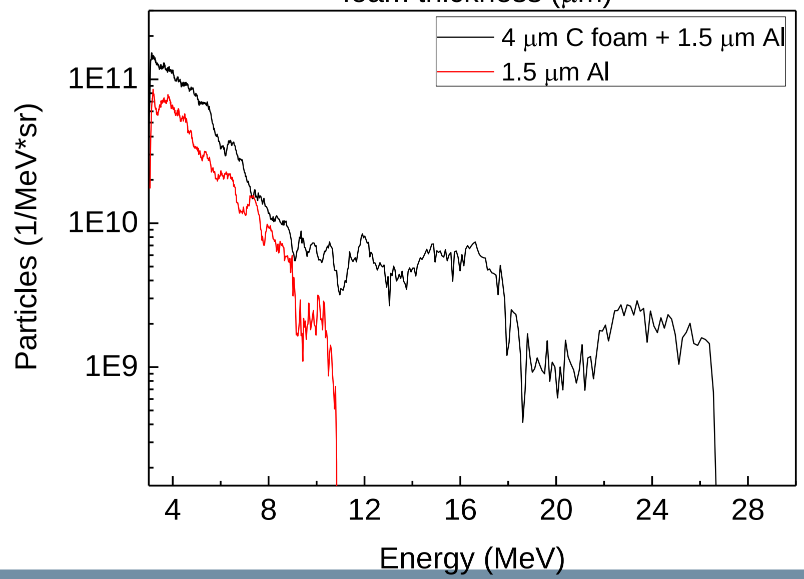
- E=200 mJ
- P=1000 Pa Ar
- d_{ts}=4.5 cm
- thickness = 4, 8, 12 µm
- Substrate = Al 1.5 µm



Ion acceleration: laser parameters

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



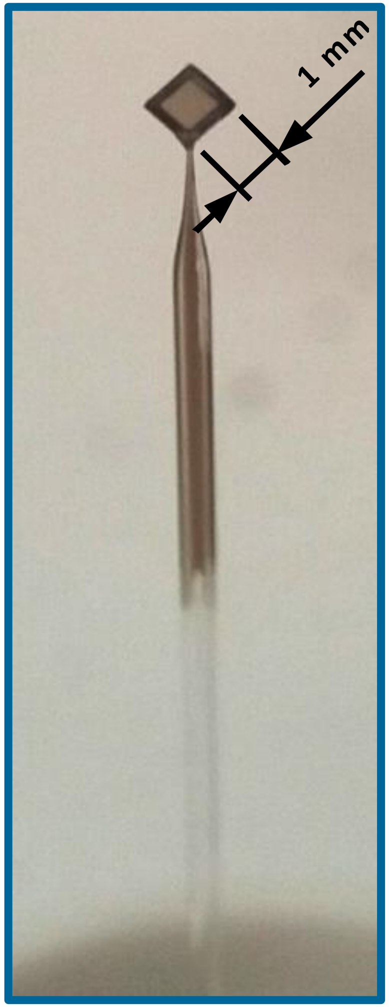


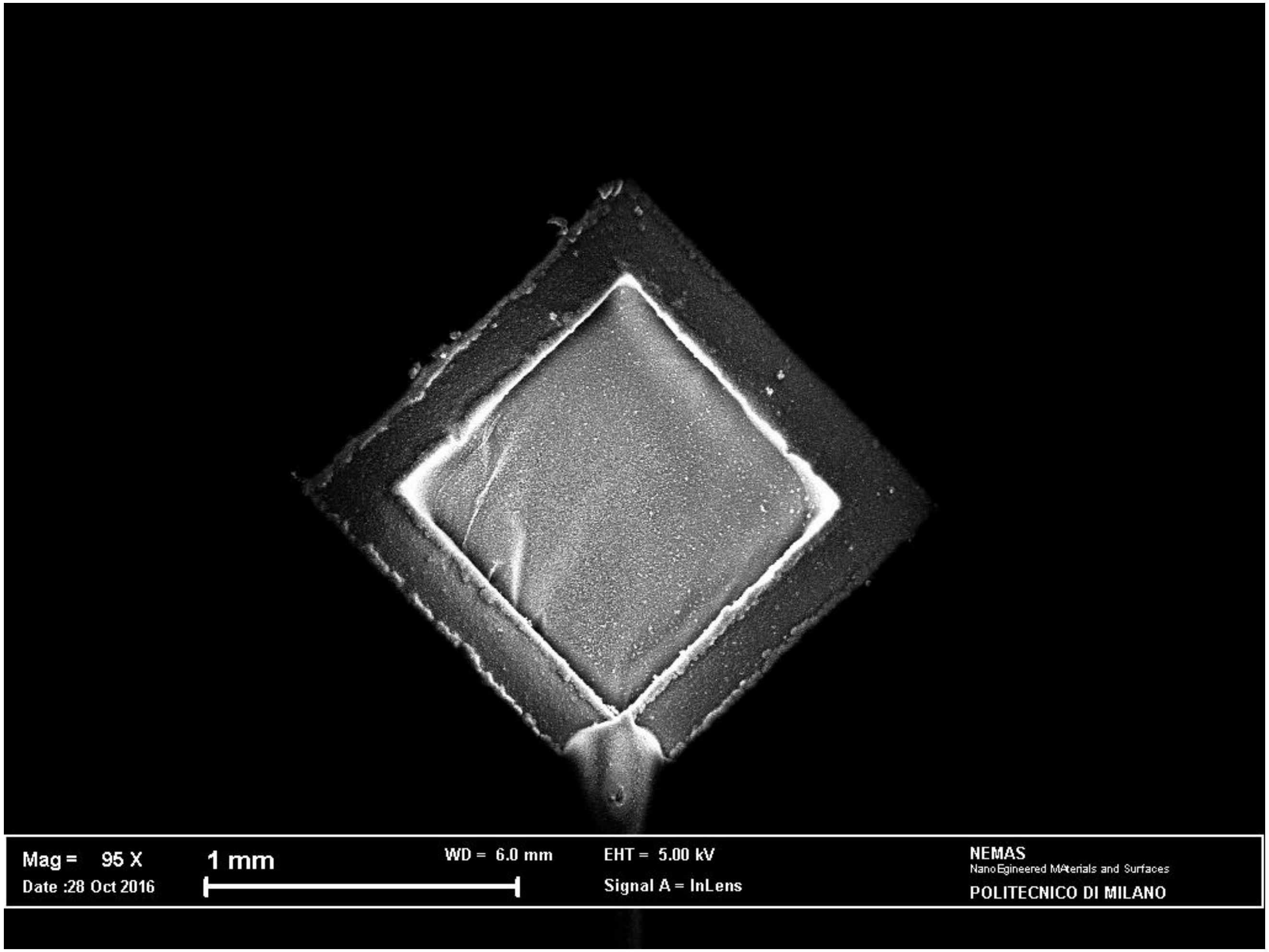
New multilayer target development

in collaboration with:
A. Morace

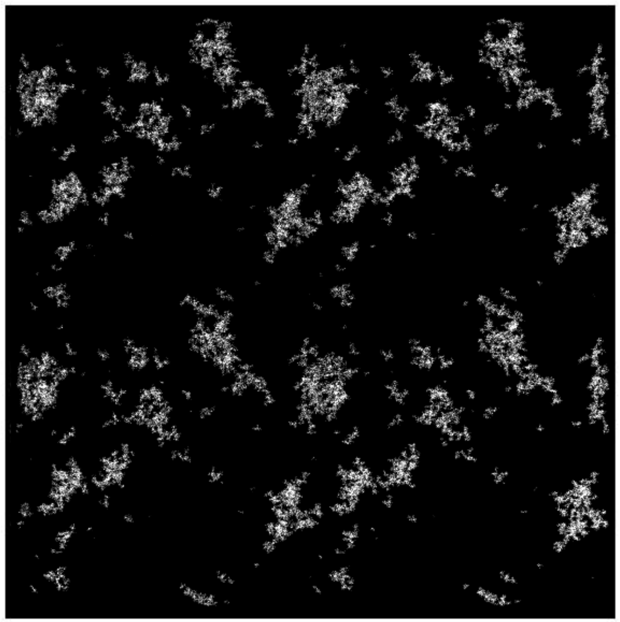
OSAKA UNIVERSITY

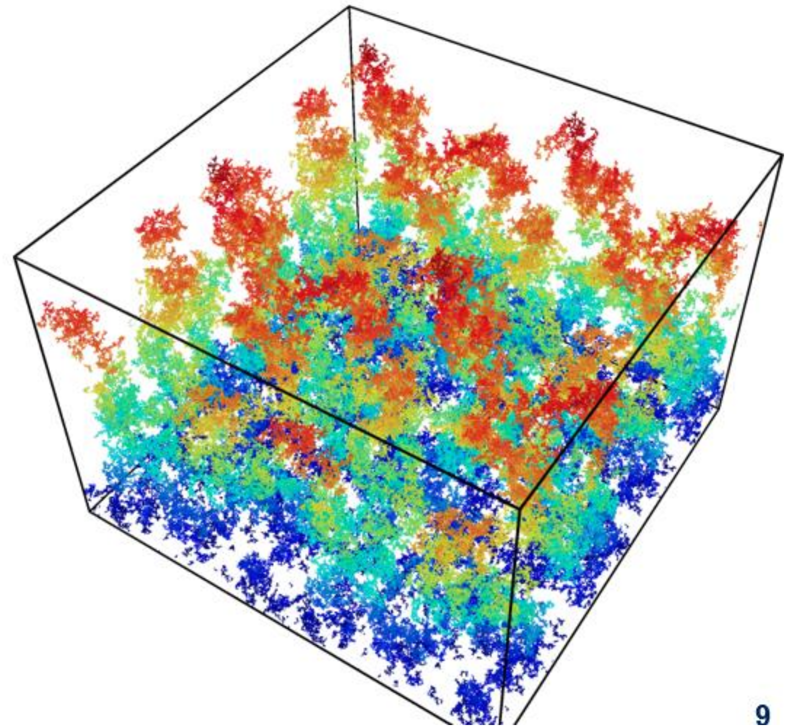
Double side deposition on a ultra-thin C layer (100 nm)
Interest: laser induced electrostatic shock generation





For further improvement: foam growth modelling



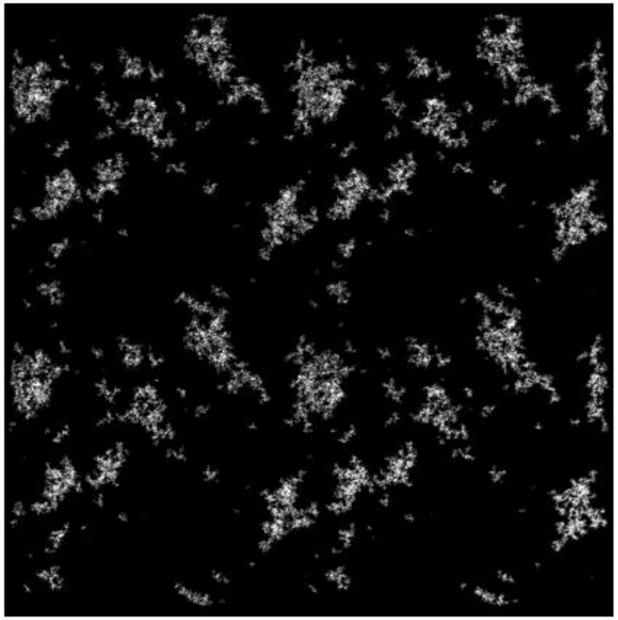


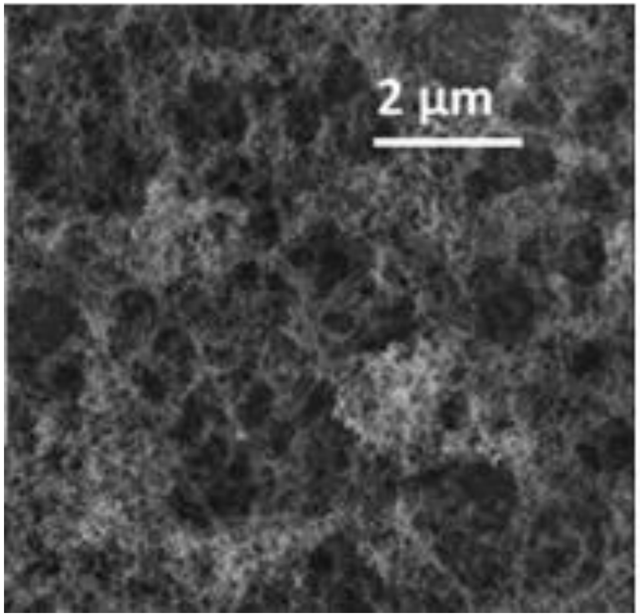
9

Diffusion limited cluster-cluster aggregation model

Nanoparticles aggregate before reaching the surface

For further improvement: foam growth modelling





Diffusion limited cluster-cluster aggregation model

Nanoparticles aggregate before reaching the surface

Density gradients

~10 mg/cm^3

~150 mg/cm^3

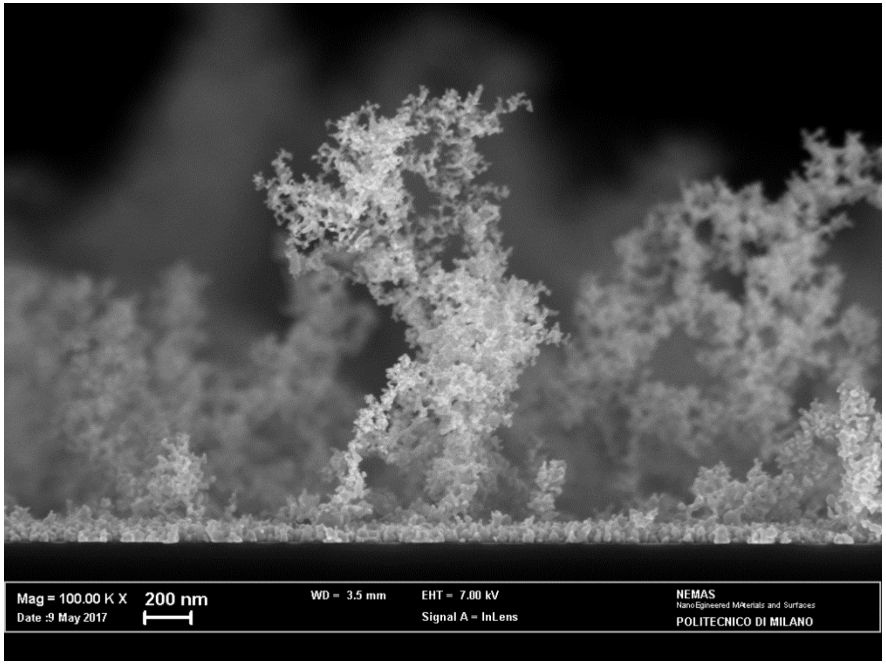
Foam: PLD parameters

- E=150 mJ
- P= from 100 Pa to 700 Pa Ar
- d_{ts}= 4.5 cm

Gold foams

Foam: PLD parameters

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



Conclusion

- Production of multilayers targets composed of near critical carbon foam 4 um thick
- Promising results in laser ion acceleration experiments

Near future developments

- **Foam brittleness**: further improve the target holder to allow a higher density of shots using thin foam
- Production of targets with **density gradients & different composition** (e.g. C-H or C-D; high Z materials)
- Multi-layered targets exploiting capabilities also of **fs-pulsed laser deposition (foam)** and **High Power Impulse Magnetron Sputtering (substrate)**
- **Theoretical and numerical modelling** of foam formation and growth, to be used also for reliable PIC numerical analysis of the **laser-foam interaction physics (see L. Fedeli next talk)**
- Production of **prototype foam-based target systems** to be used in compact interaction chambers
- On site production of foam targets with a suitable PLD laser?

Thank you for your attention!

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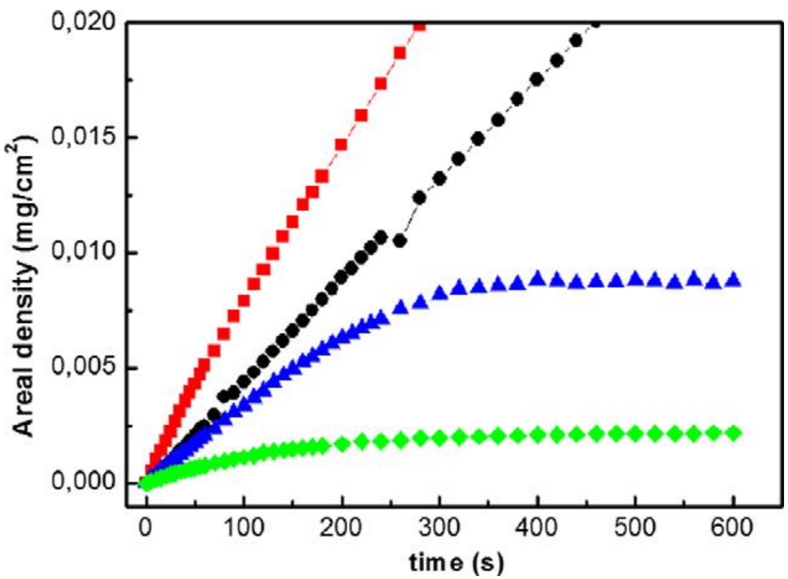
More info on our website

www.ensure.polimi.it

How to measure film density?

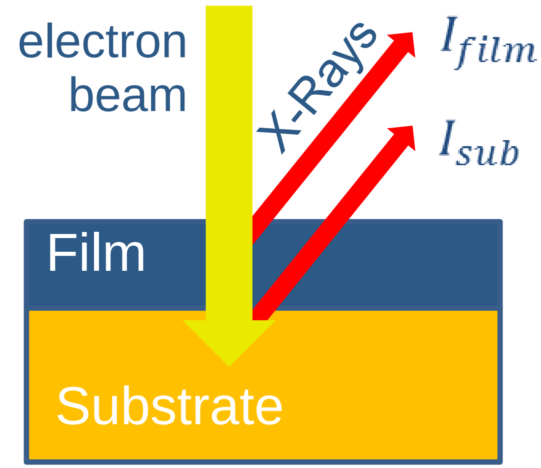
Quartz microbalance



does not work!

loss of stiffness of the film

Scanning Electron Microscopy (SEM) +
Energy Dispersive X-Ray Spectroscopy (EDS)



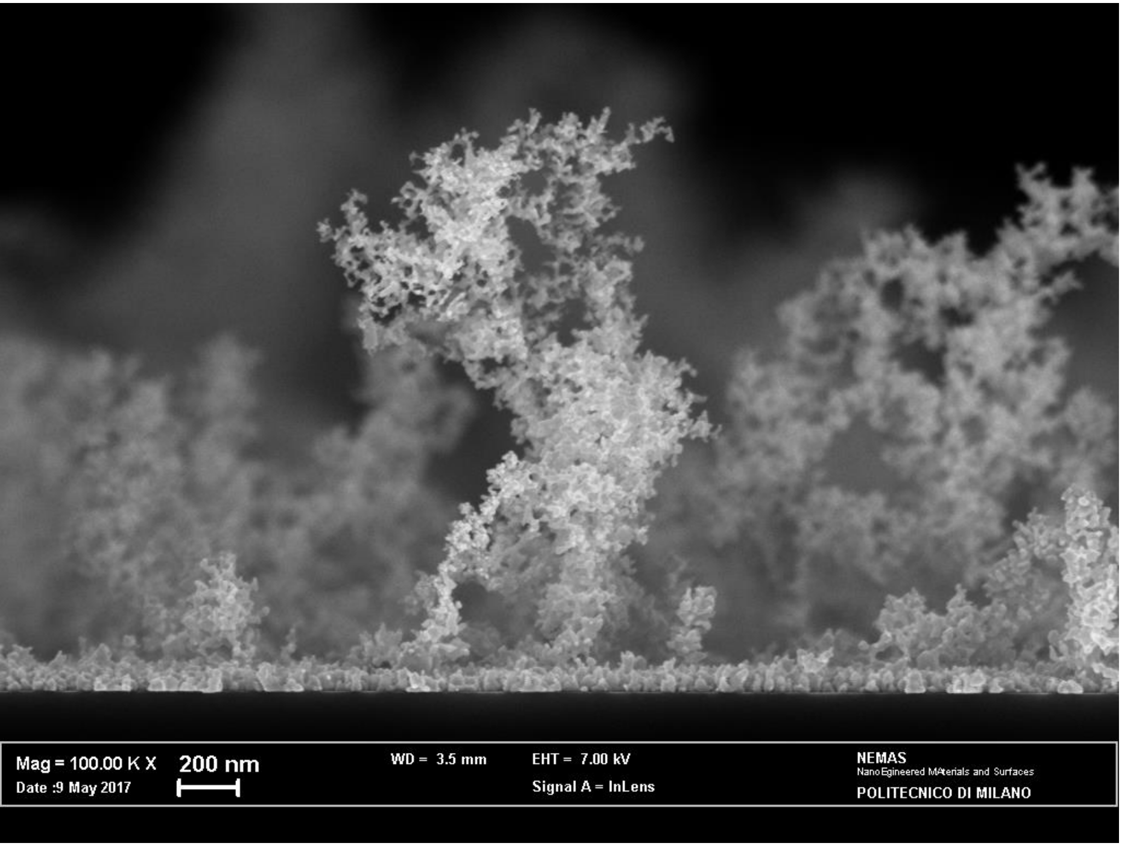
$$\frac{I_{film}}{I_{ref,film}} = f(\rho, z)$$

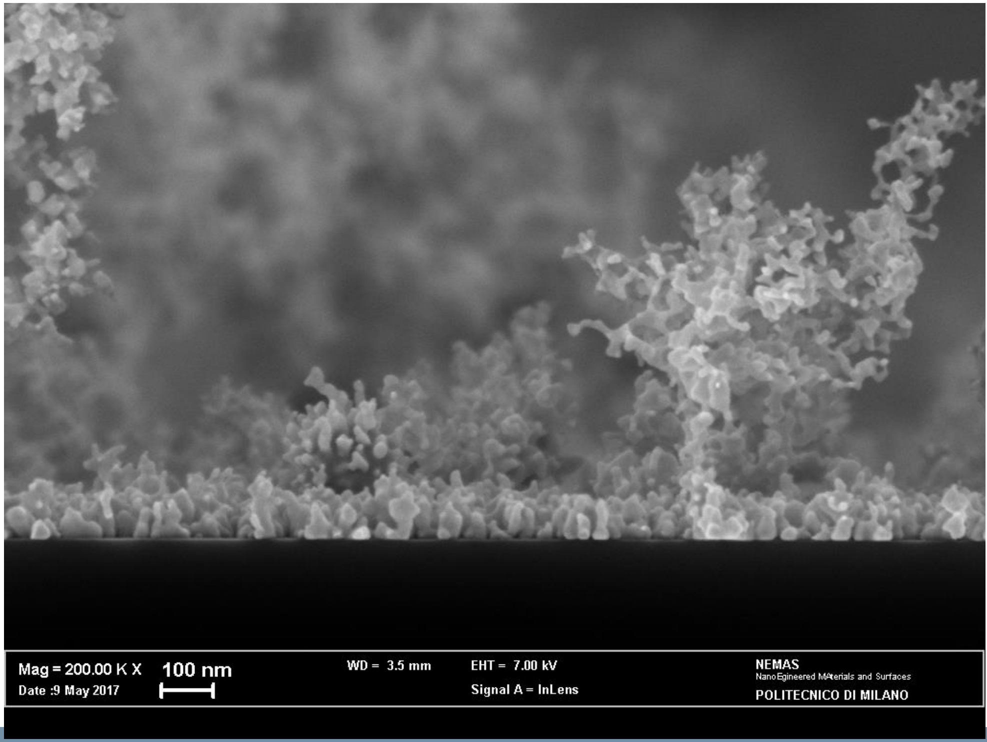
areal density calculation

density measurement of nanostructured films

I. Prencipe *et al.*, Sci. Technol. Adv. Mater., 16, 025007 (2015)

Towards high Z materials – gold foams

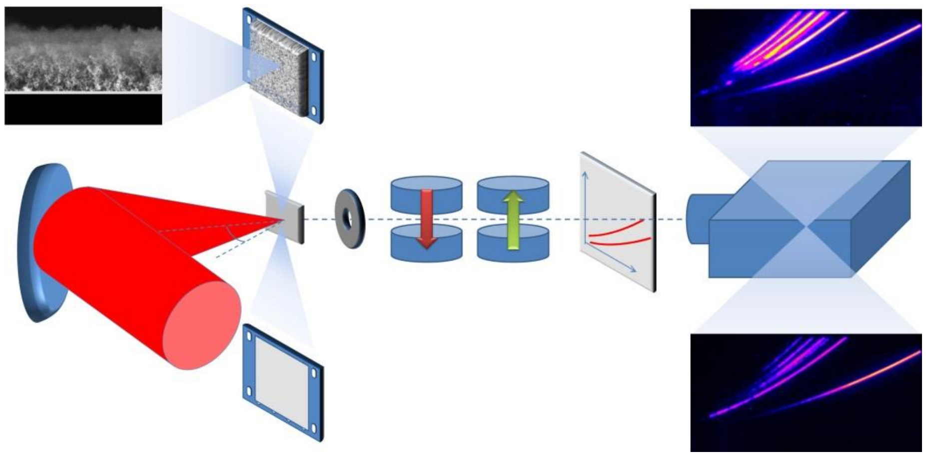


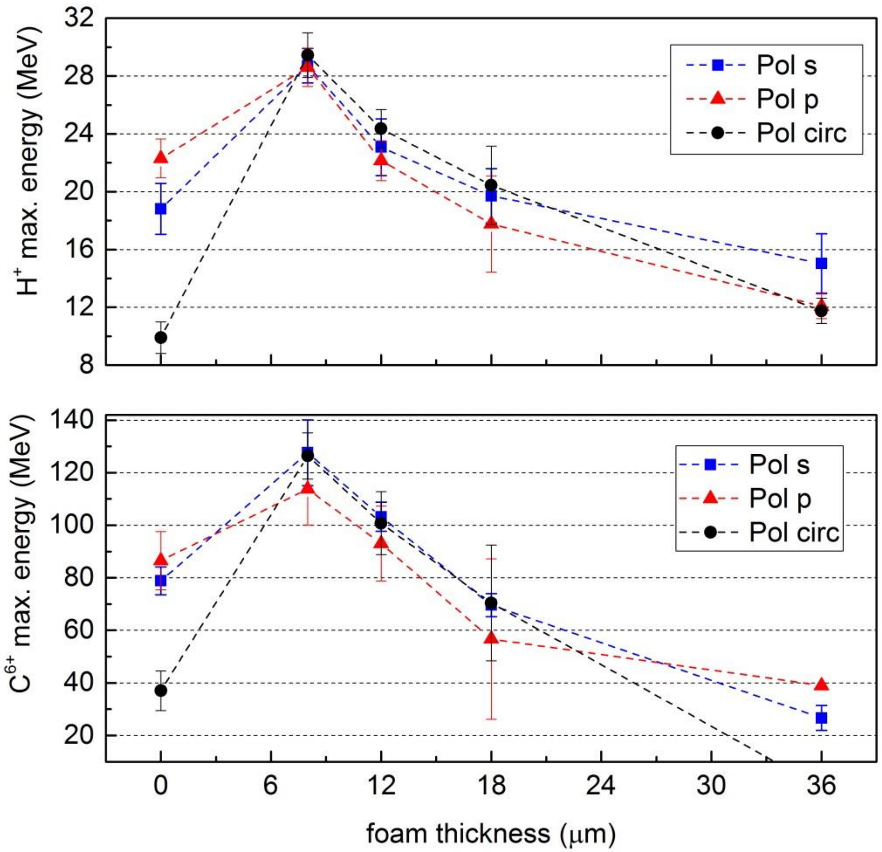


Gold foam

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

Acceleration experiment @ GIST





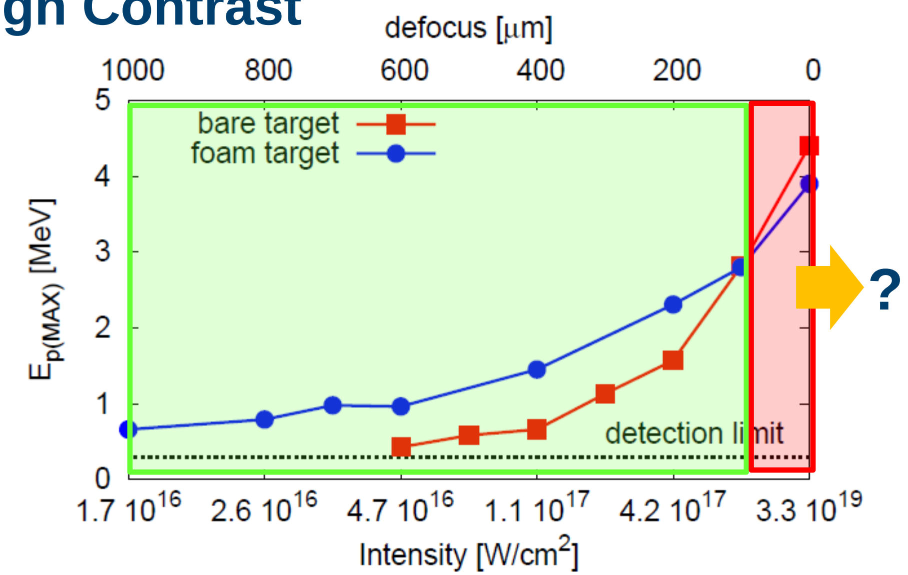
PULSER laser at GIST
(Gwangju, South Korea)
$I \sim 5 \times 10^{20}$ W/cm^2, $T_{FWHM} \sim 25$ fs

Acceleration experiment @ UHI100 LIDyL

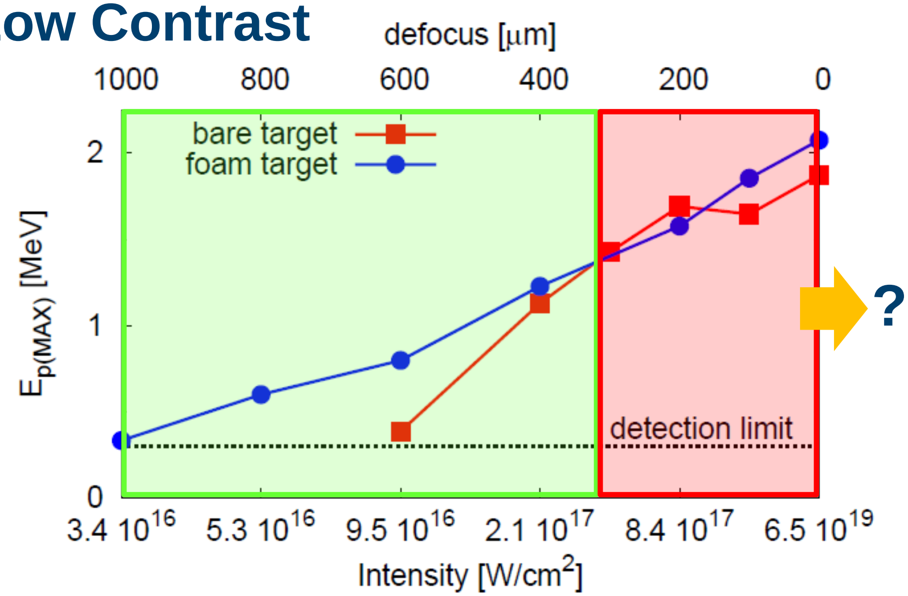
M. Passoni *et al.*, Plasma Phys. Control. Fusion, 56 045001 (2014)

in collaboration with:
P. Martin, T. Ceccotti et al.

High Contrast



Low Contrast



two interaction regimes

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

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

Enhanced proton acceleration regime

$I\sim10^{18}$ - 10^{19} W/cm^2

Complete foam ionization (C^{6+}): over-critical plasma

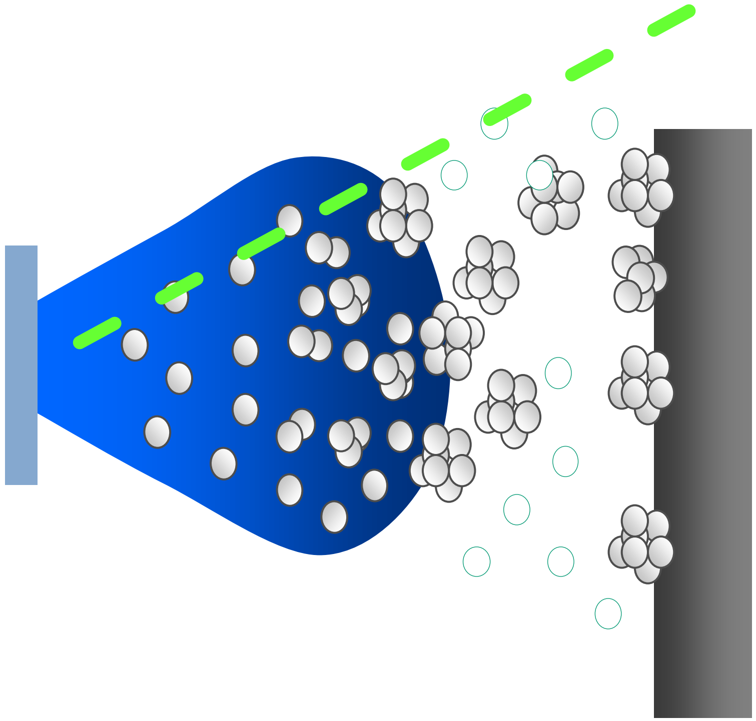
Ordinary proton acceleration regime

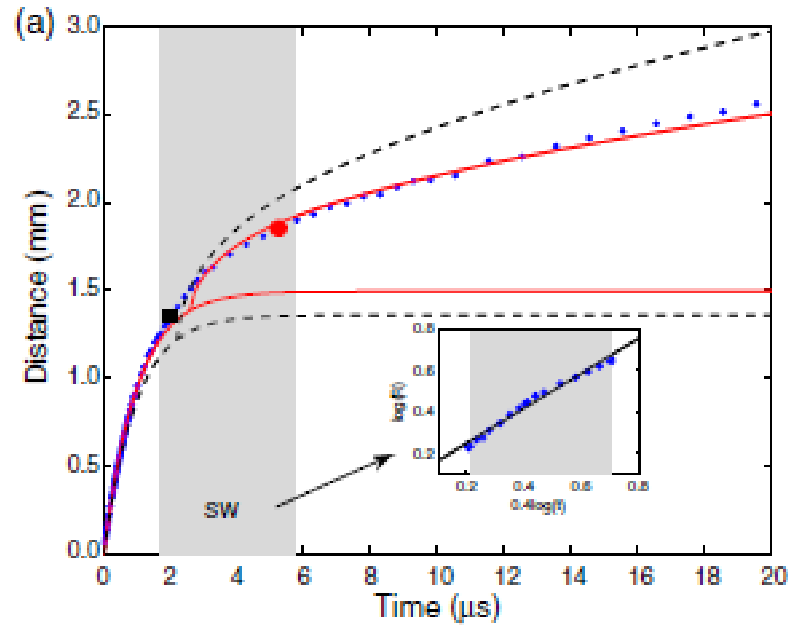
$$n_e(\rho, Z) = \rho \cdot \frac{Z}{A} \cdot N_A$$

$$n_c(\lambda) = \frac{\epsilon_0 \cdot m_e}{e^2} \cdot \frac{4\pi^2 c^2}{\lambda^2}$$

$$\frac{n_e(\rho, Z)}{n_c(\lambda)}$$

Nanoparticle formation by ns PLD in background gas





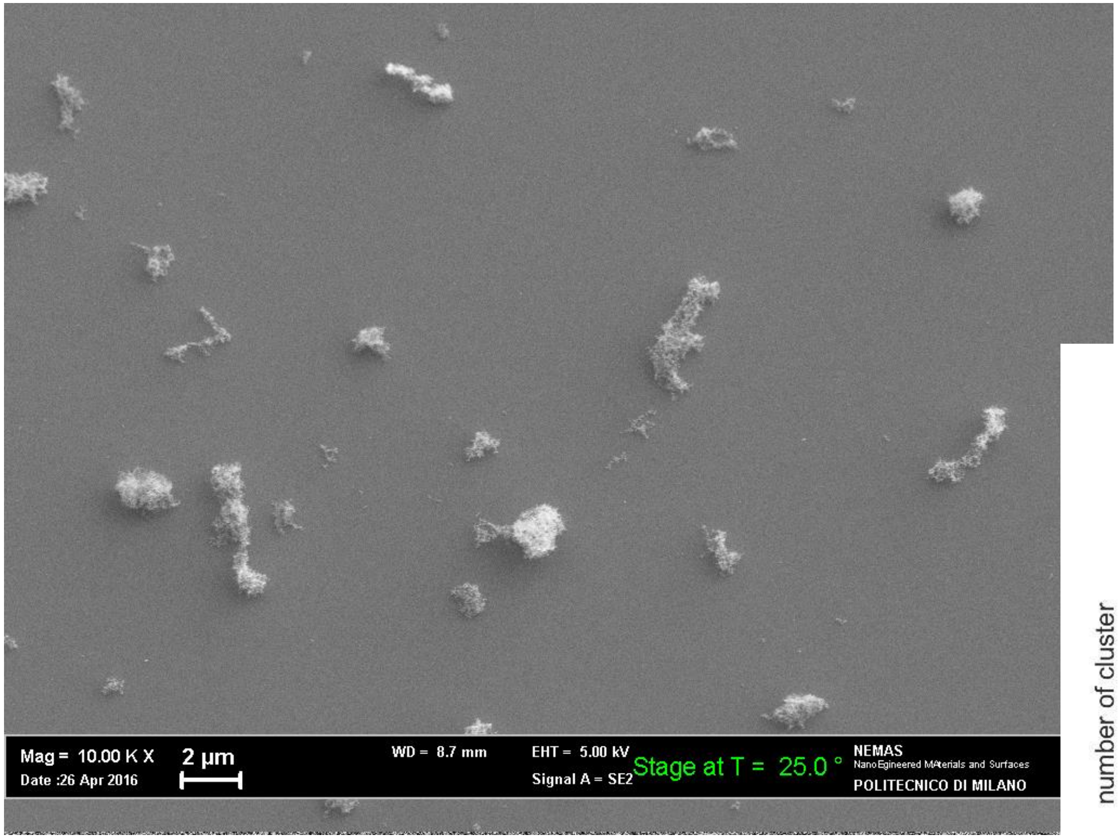
F. Neri , et al. Radiation Effects and Defects in Solids, 165:6-10, 559-565 (2010)

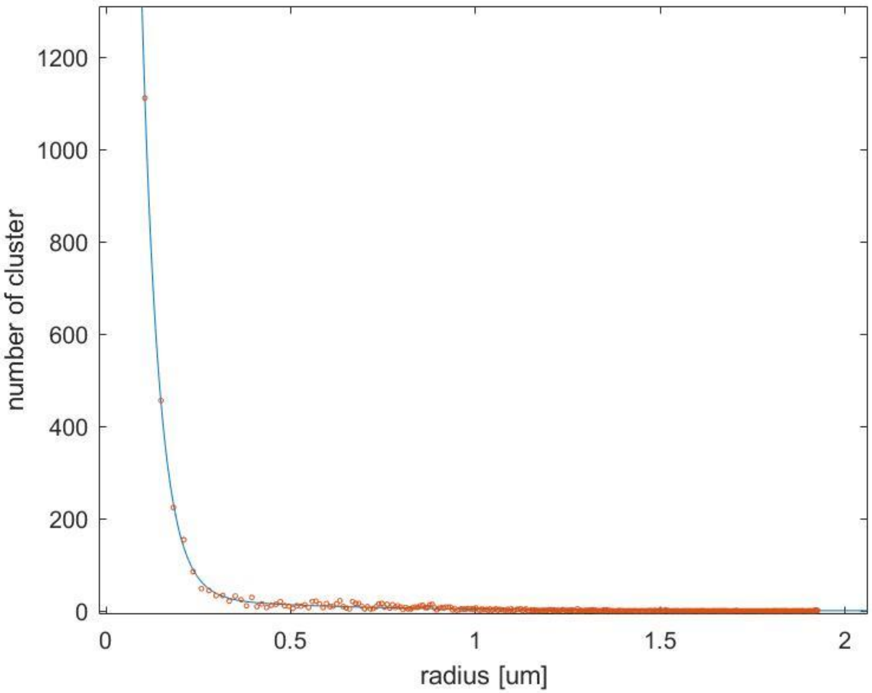
1. Adiabatic expansion
2. Shock wave formation
3. Nanoparticle synthesis
4. Nanostructured film formation

Many models are used to describe plume dynamics (drag model, shockwave model, diffusion model)

It is not possible to use a unique model for describing the whole process

Diffusion limited cluster-cluster aggregation model for foam deposition





Diffusion limited cluster-cluster aggregation model for foam deposition