Investigation of near-critical foam targets for laser-driven ion acceleration

Irene Prencipe

6th Target Fabrication Workshop
Greenwich, May 2017

Acknowledgments

Nanolab @ Politecnico di Milano

- Advanced targets for laser driven ion sources
- Target fab, PIC, experiments
- Beamline application: material science

ERC-2014-CoG
No. 647554

Laser-particle acceleration group

- DRACO 150 TW/1 PW (Ti:Sapphire, 30 fs)
- Beamline application: cancer therapy (soon in vivo)

HZDR High Energy Density group

- HI/HE lasers @ European XFEL
- fs probing of laser-driven plasmas on the few nm scale by Small Angle X-Ray Scattering

Access to the characterization capabilities of the Institute of Ion Beam Physics and Material Research

HZDR

Target Normal Sheath Acceleration (TNSA)

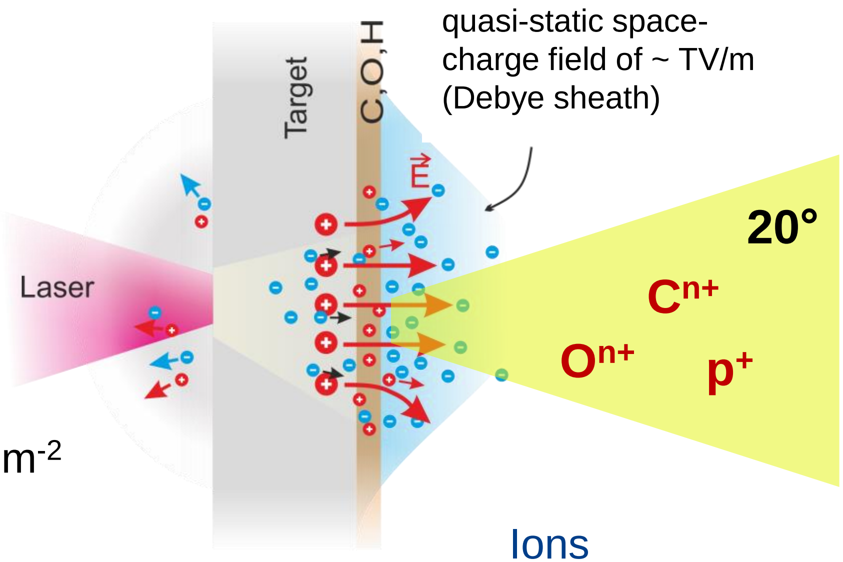
Laser

Ti:Sapphire ~ 30 fs

100 TW-1PW

I ~ $2x10^{16}$ - 4.5×10^{20} Wcm^{-2}

Potentially 1-10 Hz



Ions

- 10s MeV/nucleon
- 10^{11} – 10^{13} particles/pulse
- ps pulse duration at the source
- exponential spectra

A. Macchi et al., Rev. Mod. Phys., **85** 751 (2013)

HZDR

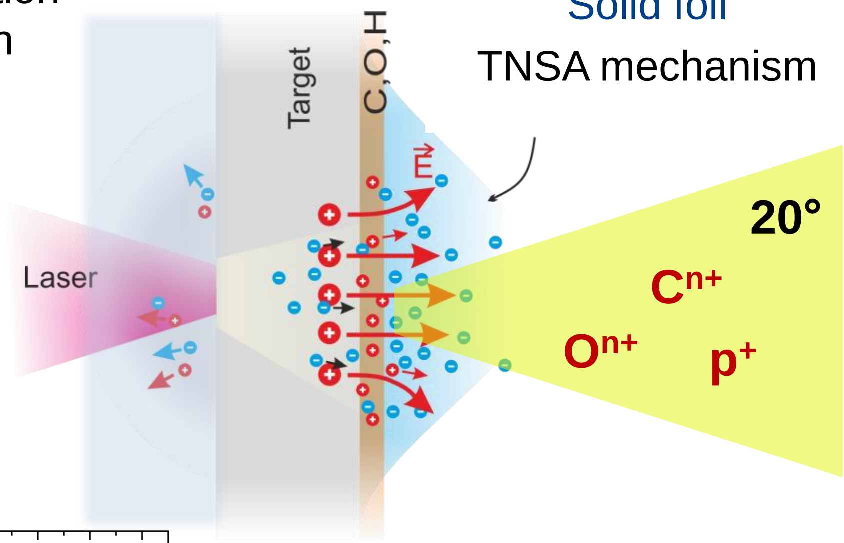
Enhanced laser absorption in near-critical layer

Low-density layer

Increased absorption and hot electron generation

Solid foil

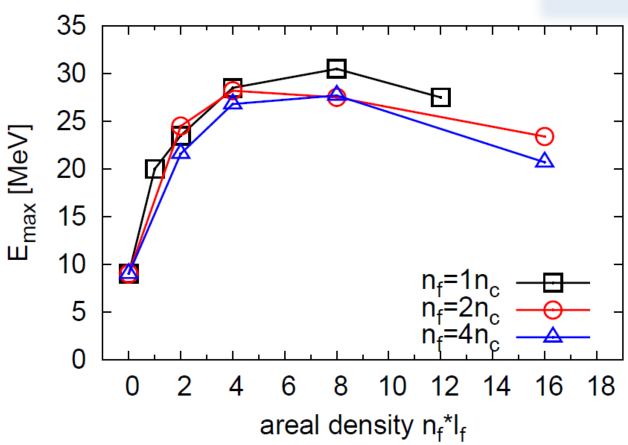
TNSA mechanism



2D PIC simulations

Density ~ n_c

Thickness ~ 10 µm



Mass density ~ 5.7 mg/cm^3 for C^{6+}, λ=800 nm

(graphite density ≈ 2 g/cm^3)

T. Nakamura *et al.*, Phys. Plasmas, **17** 113107 (2010)
A. Sgattoni *et al.*, Phys. Rev. E, **85** 036405 (2012)
J. H. Bin, Phys. Rev. Lett., **115** 064801 (2016)

Target production

ns Pulsed Laser Deposition (PLD) in background gas

Nd:Yag laser

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

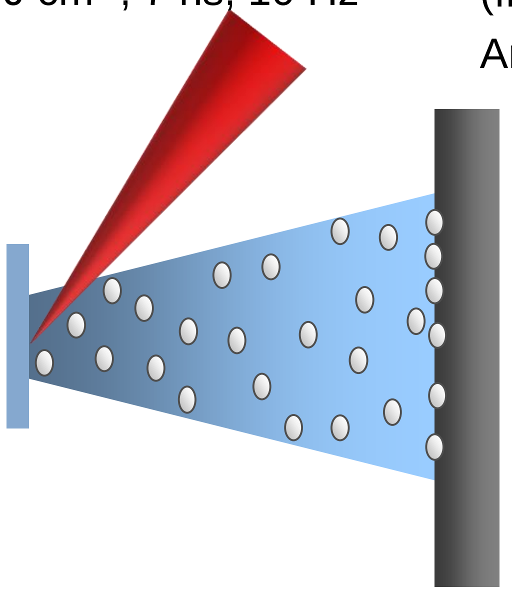
Background gas

(film structure)

Ar-He, pressure up to 1000 Pa

PLD Target

Pyrolitic graphite



Substrate

Thickness down to 10s nm

Diameter up to 5 cm

Rotation few rpm (film thickness profile)

Target-substrate distance

(film structure)

45-85 mm

Process duration

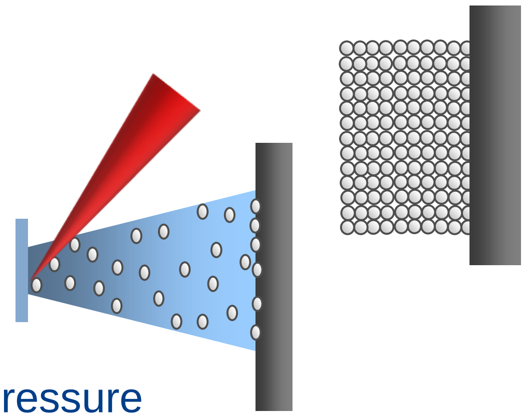
(film thickness)

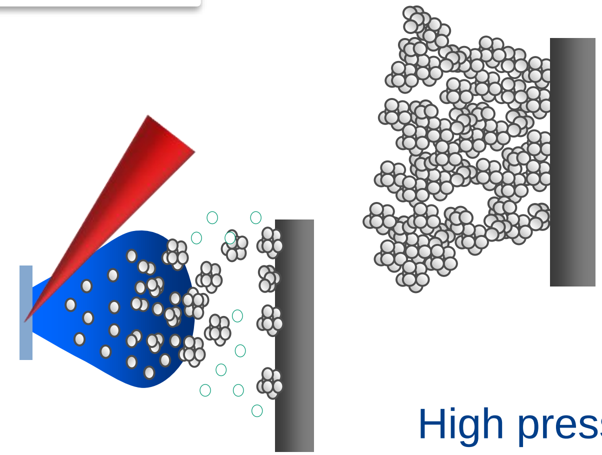
5 – 60 min

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

Target production

ns Pulsed Laser Deposition (PLD) in background gas





Low pressure

High kinetic energy

Atom-by-atom deposition

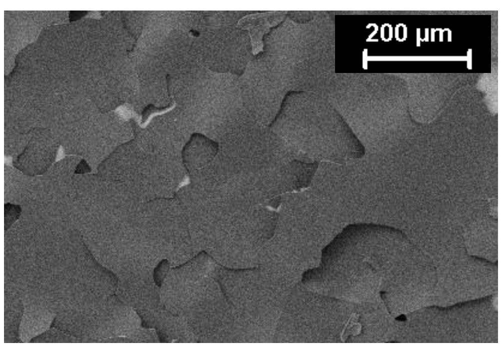
Pressure →

High pressure

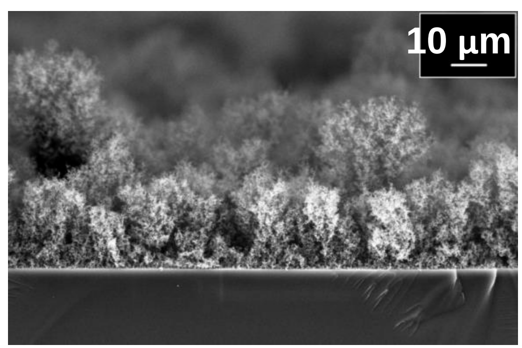
Low kinetic energy

Cluster formation

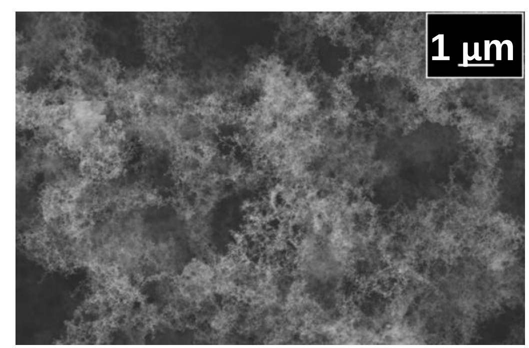
Vacuum



Ar 30 Pa



Ar 150 Pa



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

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ns Pulsed Laser Deposition (PLD) in background gas

Density gradient

Obtained by linear increase of background pressure (100 Pa to 700 Pa)

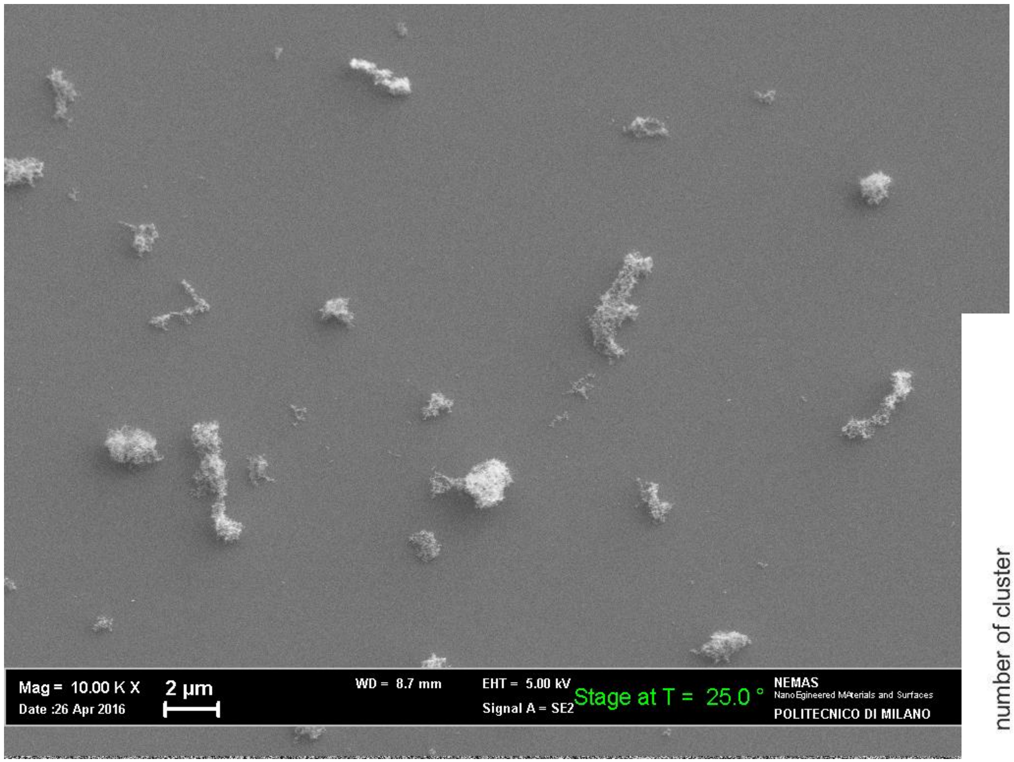
~10 mg/cm^3

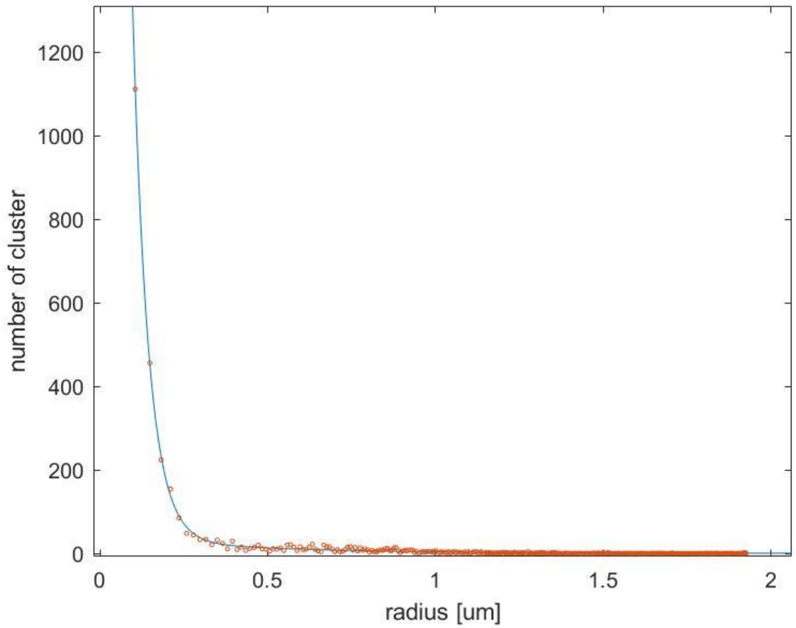
~150 mg/cm^3

Ar, λ = 532 nm, E = 150 mJ, Substrate-Target distance = 4.5 cm

HZDR

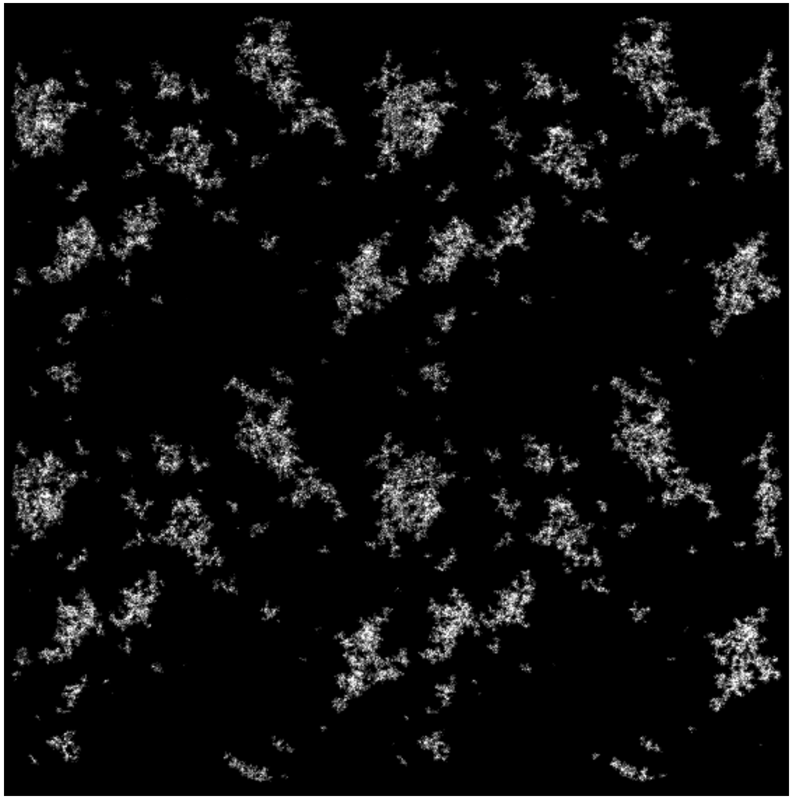
Diffusion limited cluster-cluster aggregation model for foam deposition

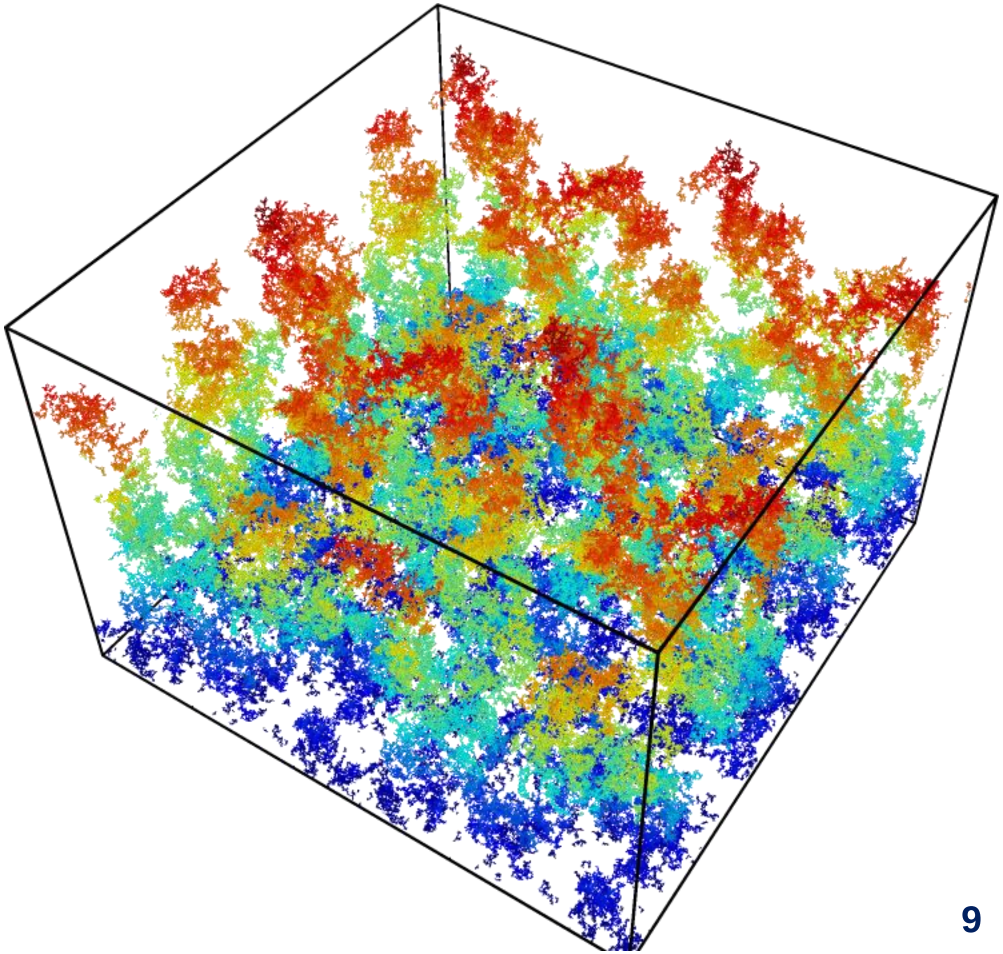




Target production

Diffusion limited cluster-cluster aggregation model for foam deposition

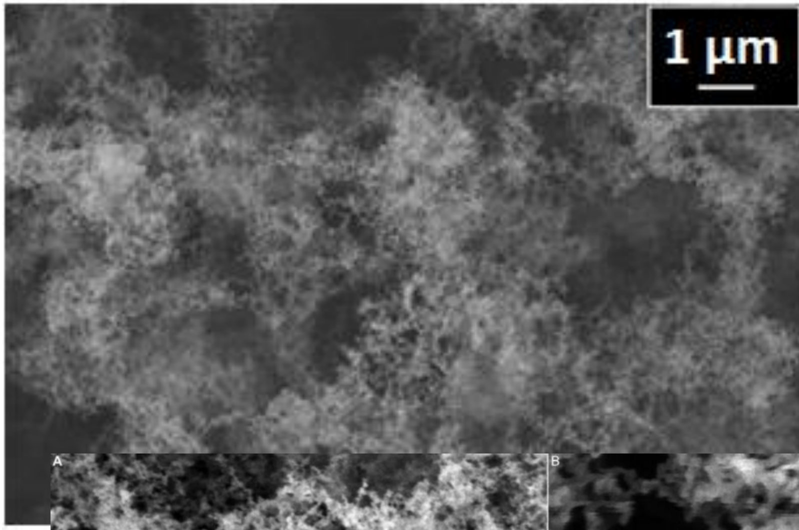




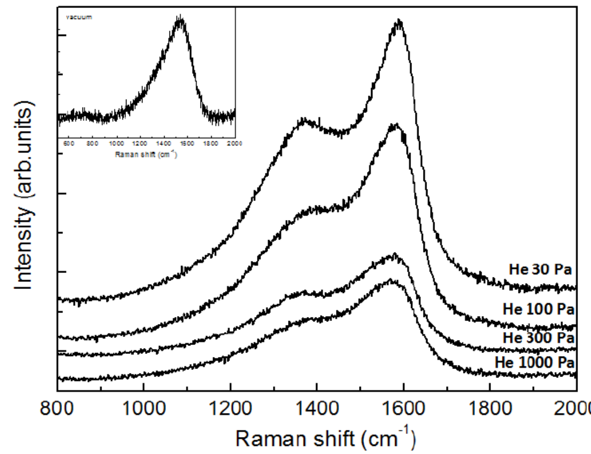
Target characterization

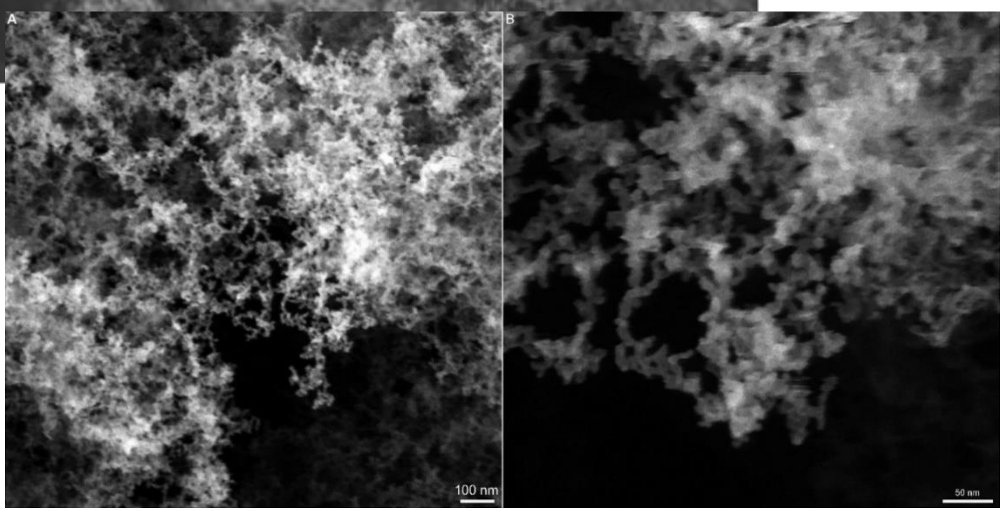
Morphology and nanostructure

Scanning Electron Microscopy



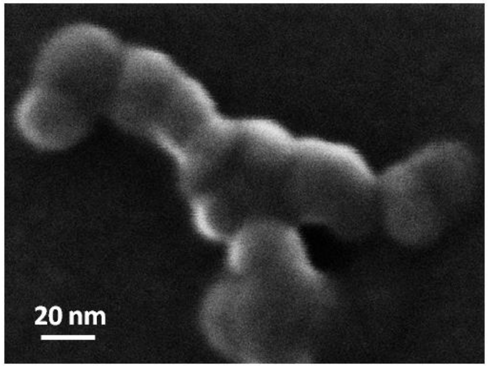
Raman Spectroscopy





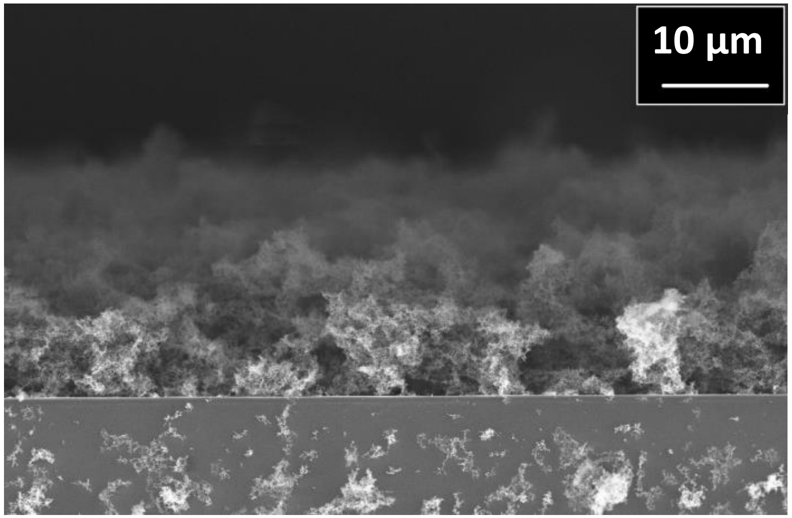
He Ion Microscopy @ IBC-HZDR

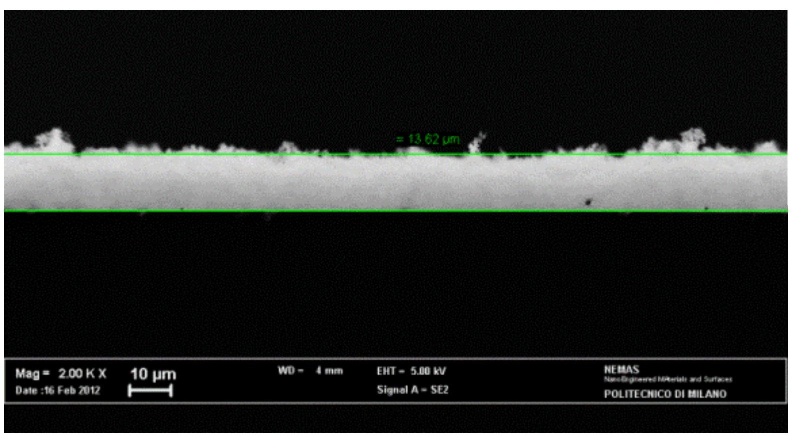
Scanning Transmission Electron Microscopy



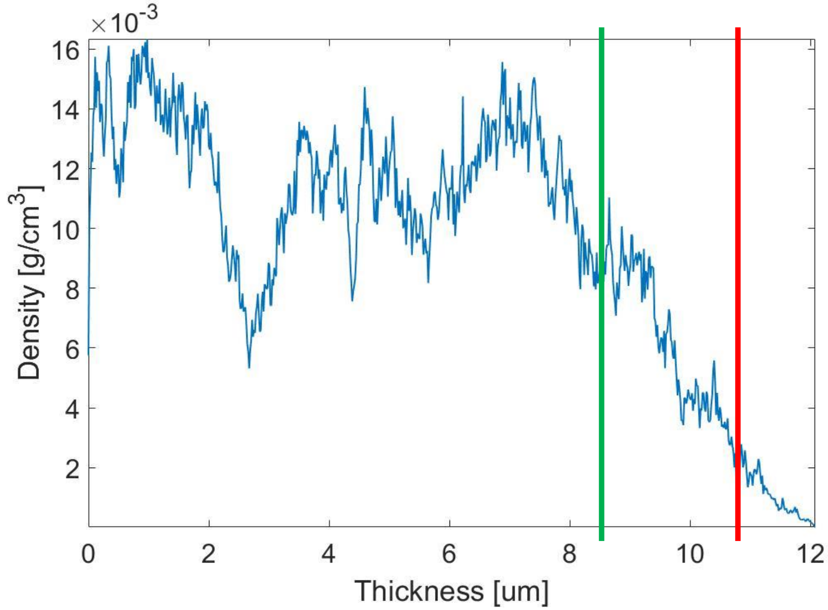
Thickness

Cross Section Scanning Electron Microscopy





Diffusion limited cluster-cluster aggregation model

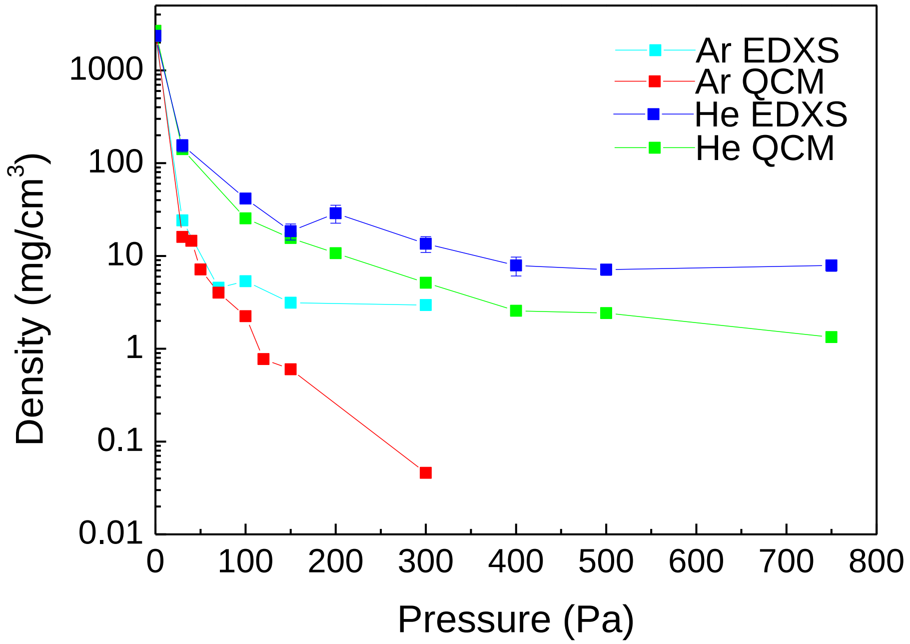


Film thickness ~ 4 µm – 80 µm

Target characterization

Density and composition

Quarz Crystal Microbalance
vs Energy Dispersive X-Ray Spectroscopy



Ion Beam Analysis (NRA and ERDA)
@ IBC-HZDR

- Density benchmark

ρ_{IBA}~13 mgcm^{-3} vs ρ_{EDS}~12 mgcm^{-3}

- Composition

  C ~ 92 at.%

  H ~ 6.3 +/- 2 at.%

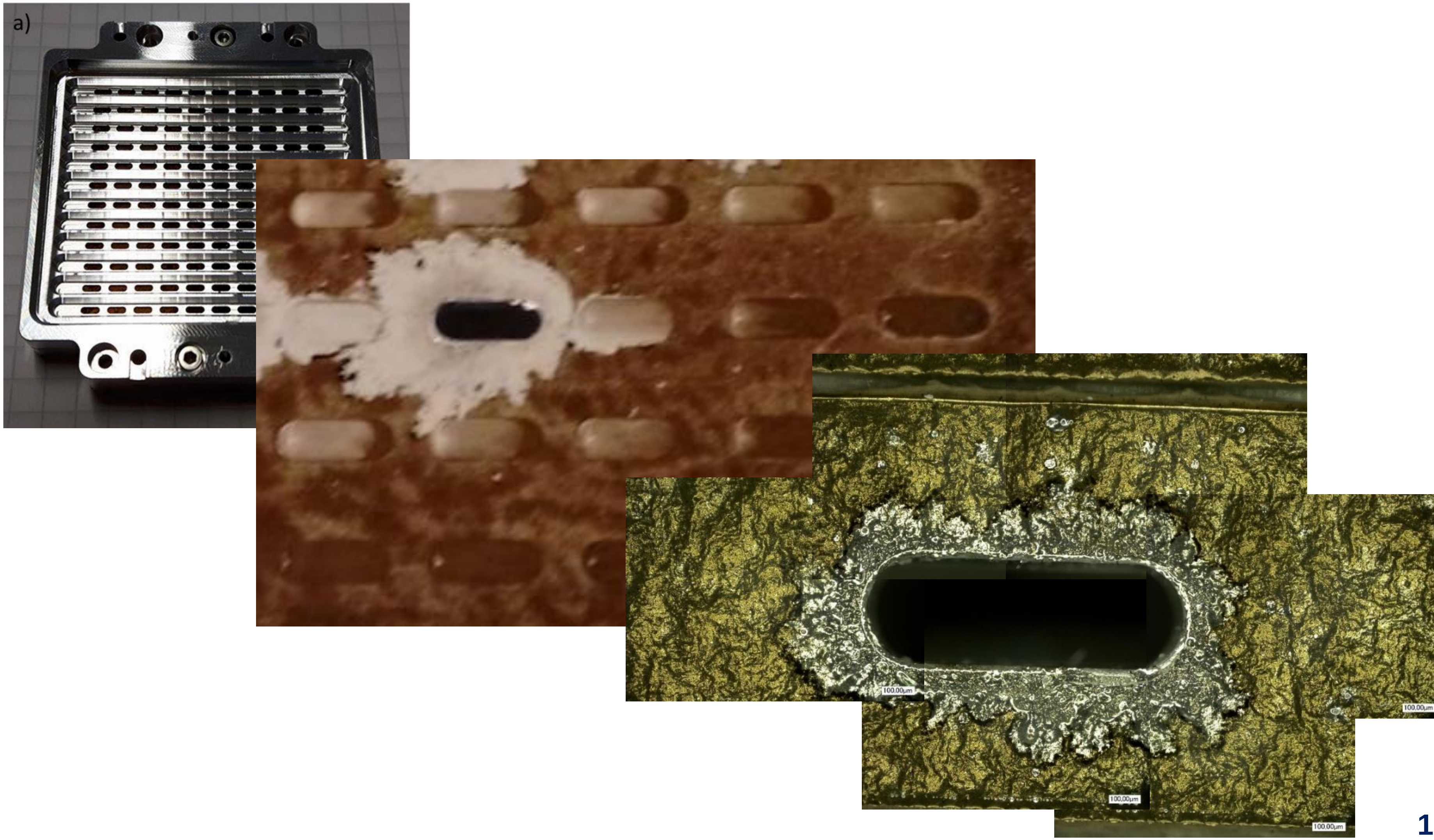
  N < 0.4 (~0.2) at.%

  O ~ 1.3 at.%

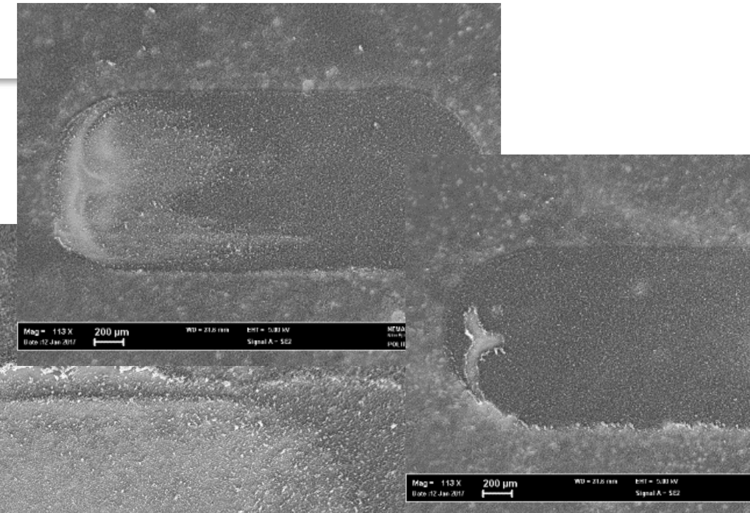
I. Prencipe *et al.*, Sci. Tech. Adv. Mat., **16** (2015)

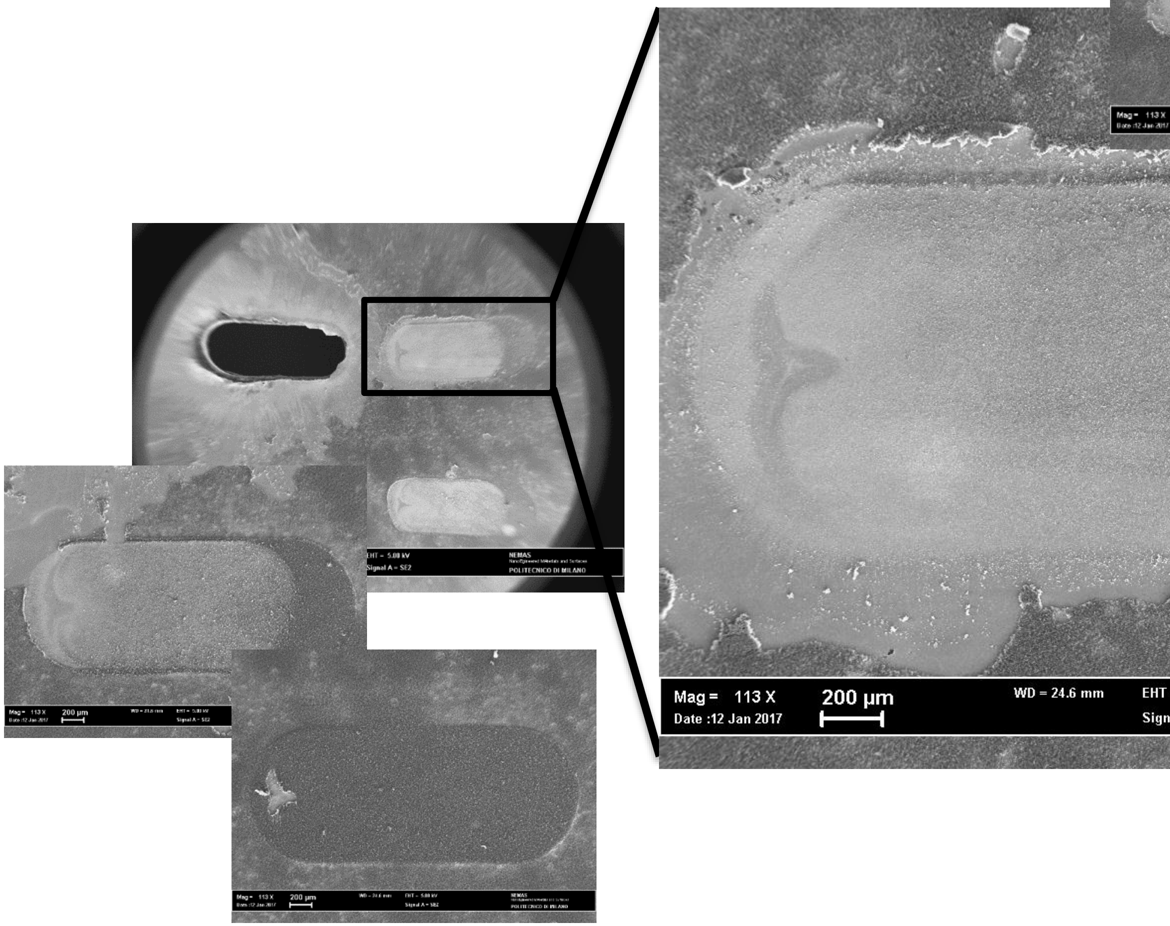
Target development

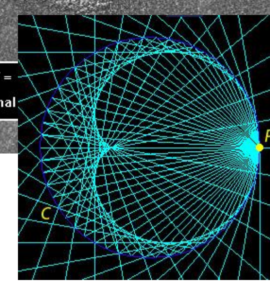
Damage in neighbouring targets @ DRACO 150 TW

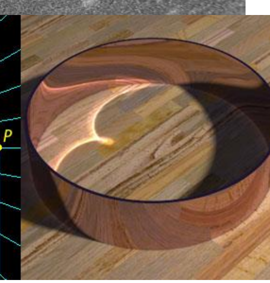


Damage in neighbouring targets @ DRACO 150 TW









Ion acceleration experiments

3 Experimental campaigns

Ti:Sapphire lasers, ~30 fs, λ=800 nm, I ~ 10^{16}-4.5 10^{20} W/cm^2

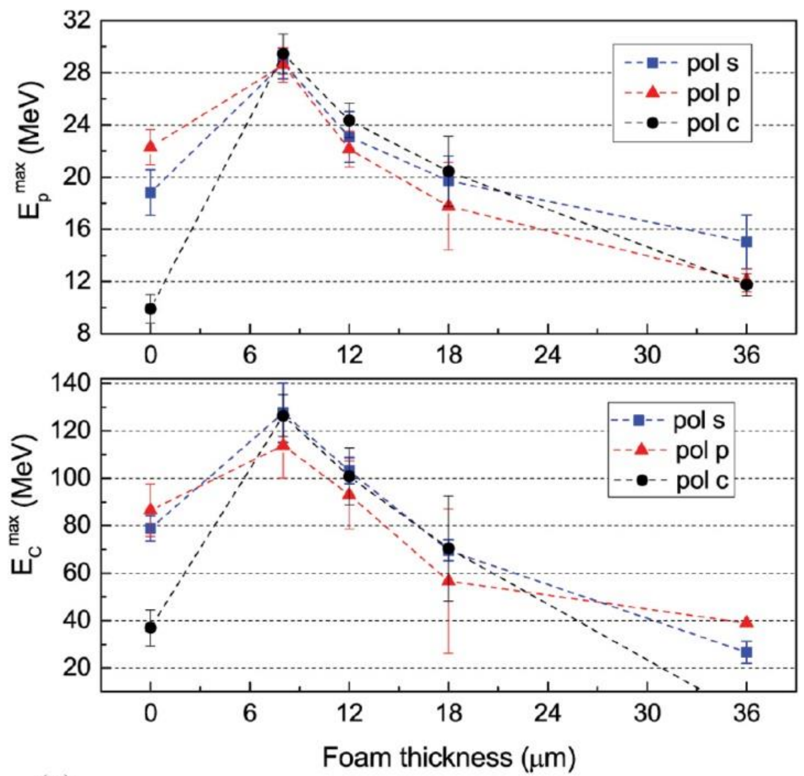
UHI100-CEA Saclay, France (2012)	CoReLs-GIST 1 PW, South Korea (2014-15)	DRACO 150 TW, HZDR, Germany (2017)
PROOF OF CONCEPT	**PARAMETRIC SCANS**	**ADDITIONAL DIAGNOSTICS**

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

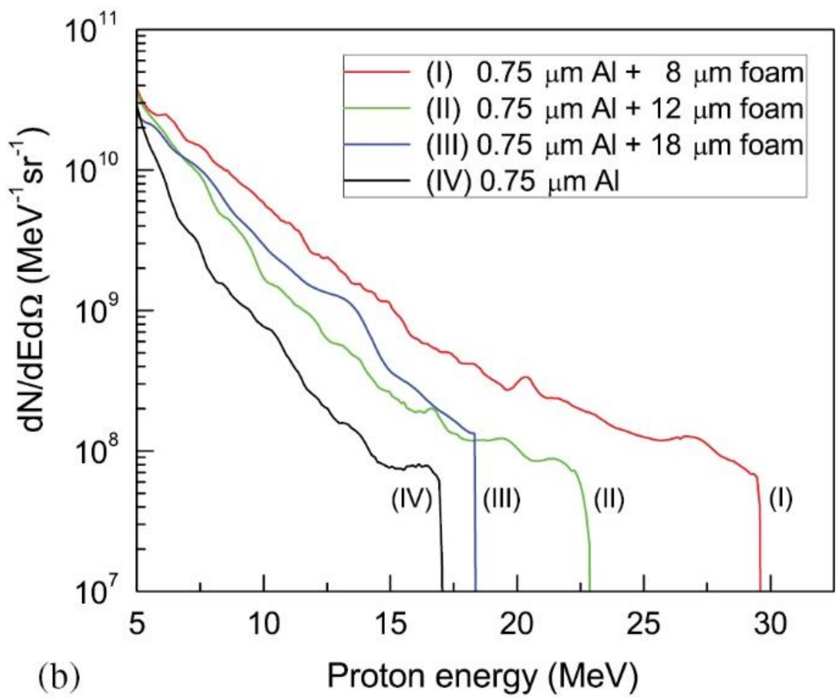
Results

Enhanced TNSA (cut-off energy, ion number)

- FOR optimal foam properties
- Reduced dependence on substrate thickness



(a)

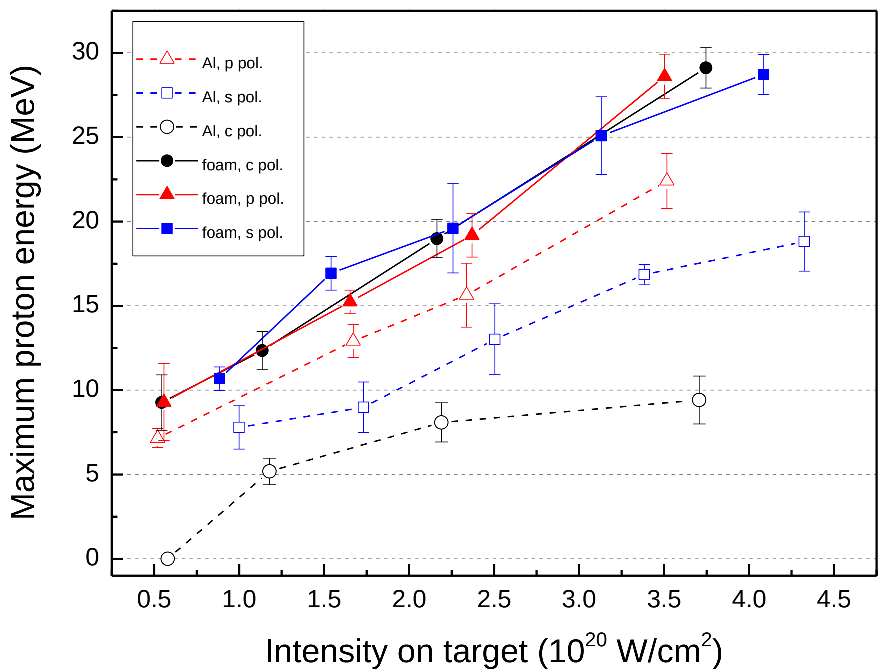


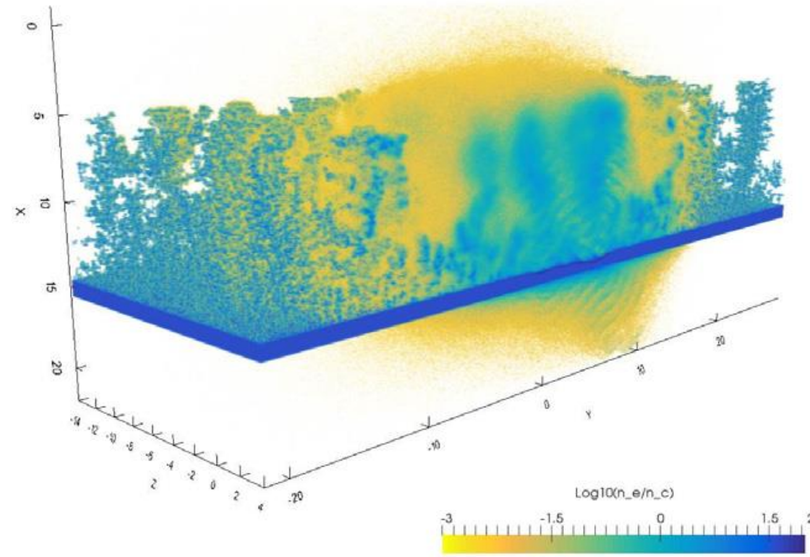
(b)

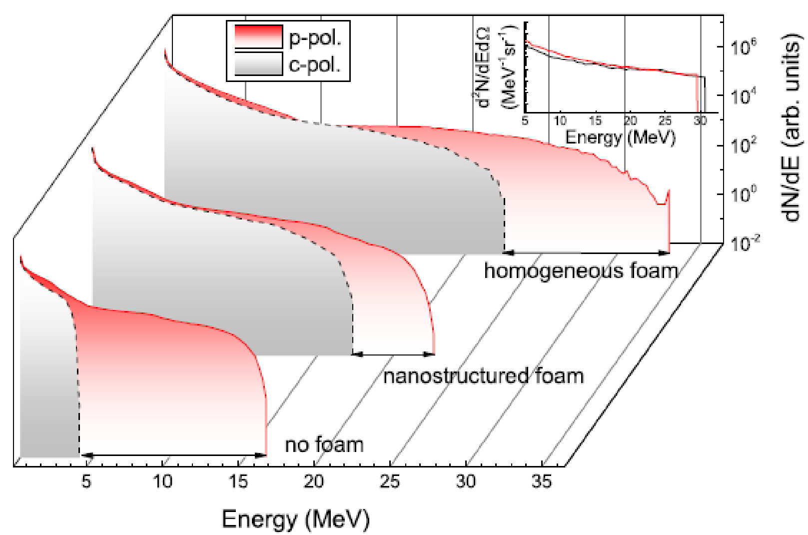
Results

Effect of foam nanostructure

- Reduced dependence on polarization







Summary

- **Target production**
  - C foam coating by ns Pulsed Laser Deposition
  - 4-80 µm, down to 7 mg/cm3
- **Target characterization**
  - SEM, EDS, QCM, STEM, Raman @ Politecnico di Milano
  - He microscopy, ERDA, NRA @ HZDR
- **Study of target damage @ DRACO, HZDR**
- **Experimental results**
  - TNSA enhancement and foam optimization
  - Role of nanostructure (3D PIC simulations)

Acknowledgments

M. Passoni, A. Pazzaglia, D. Dellasega, A. Maffini, V. Russo, L. Fedeli…

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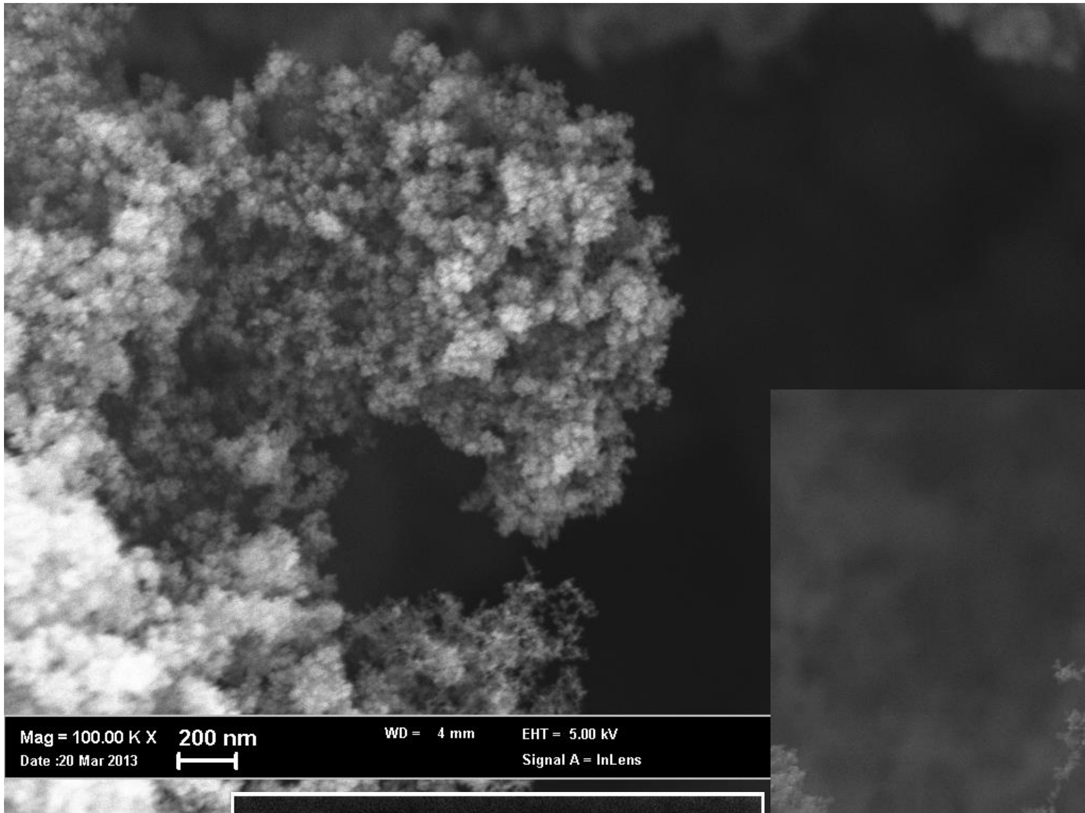
No. 647554

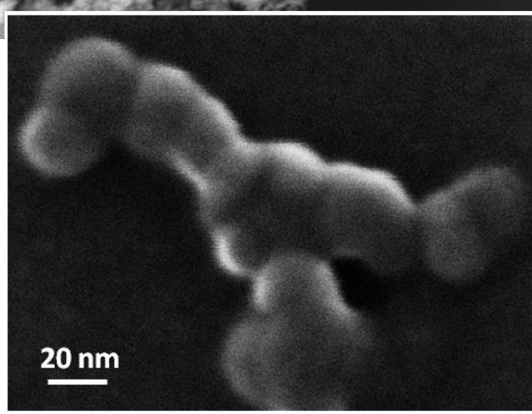
U. Schramm, J. Metzkes, K. Zeil, S. Kraft, L. Obst, M. Rehwaldt, M. Sobiella…

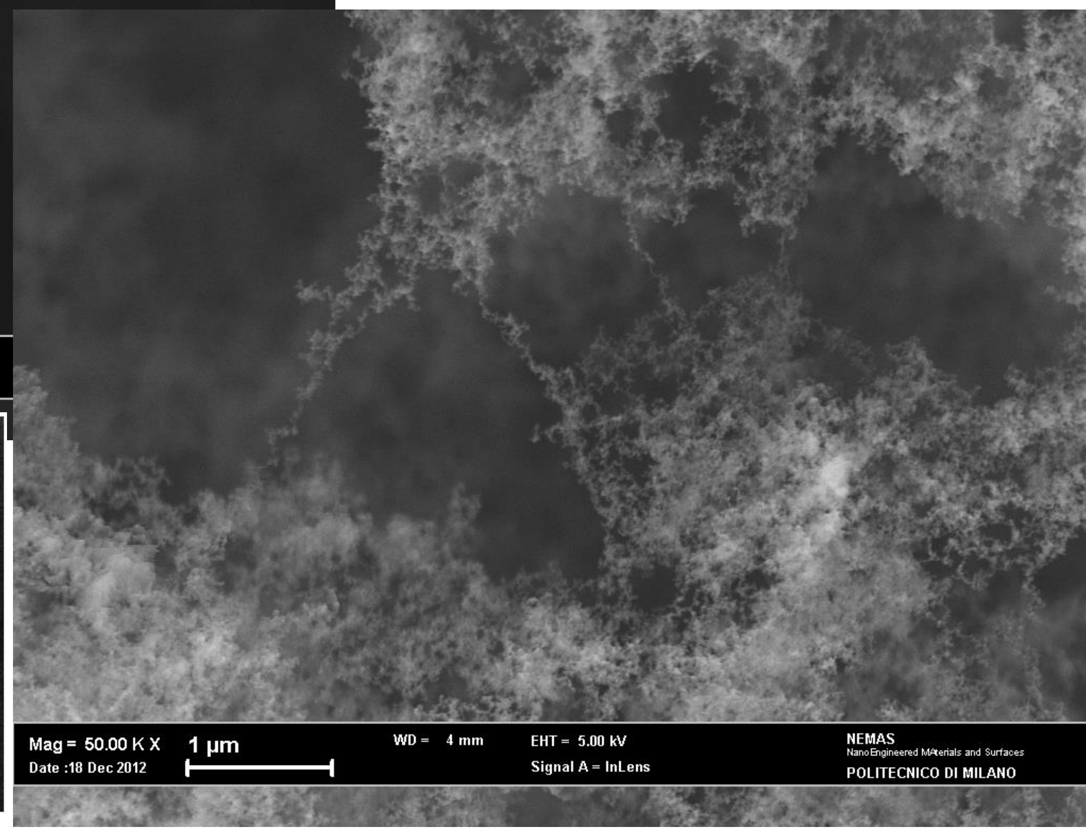
T. Cowan, A. Laso Garcia, T. Kluge, M. Molodtsova, A. Ferrari…

J. Von Borany, J. Grenzer,
G. Hlawacek, J. Julin, R. Heller

Thank you for your attention







HED Instrument at European XFEL

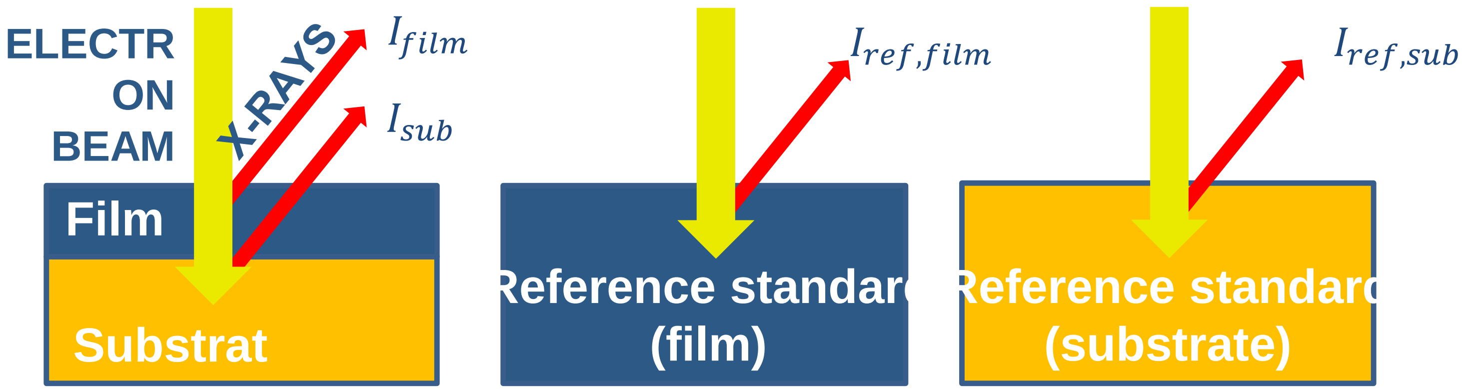
Key features

Bandwidth ΔE/E	10^{-3} (natural FEL source) and 10^{-4} (standard monochromator, seeding); 10^{-6}* (high-resolution monochromator)
Photon energy range	3–5 keV**, 5–20 keV, 20–25 keV**
Polarization	Linear (horizontal) Circular (future option)
Pulse duration	2–100 fs FWHM
Beam size	Sub-µm to > 100 µm (provided by various compound refractive lens stages) >mm unfocused
Special optics	Split and delay line (*BMBF contribution*) High-resolution monochromator
Optical lasers	High-energy (100 J-class) long pulse (>ns) laser (*HIBEF contribution*) High-intensity (100 TW-class) short pulse (~30 fs) laser (*HIBEF contribution*) Pump–probe (mJ to 100 mJ class) short pulse (~15 fs – 1 ps) laser

*10^{-6} bandwidth only for a few selected photon energies

**Limited in terms of focusing capability, available photon number of sample, quantum efficiency of detectors

Energy Dispersive X-Ray Spectroscopy (EDS)



TWO APPROACHES FOR AREAL DENSITY CALCULATION

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

COATING METHOD

$$\frac{I_{sub}}{I_{ref,sub}} = g(\rho z)$$

SUBSTRATE METHOD

CONVENTIONALLY: THICKNESS MEASUREMENT FOR COMPACT FILMS WITH KNOWN DENSITY

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

DENSITY MEASUREMENT OF NANOSTRUCTURED FILMS IN A WIDE DENSITY RANGE

I. Prencipe *et al.*, Sci. Technol. Adv. Mater., **16**, 025007 (201