46th PLASMA PHYSICS Conference

EPS 2019
July 8-12, Milan

POLITECNICO MILANO 1863

NanoLab
Department of Energy

ERC-2014-CoG No. 647554
erc ENSURE

Advanced laser-driven ion sources and their applications in materials and nuclear science

Matteo Passoni

Politecnico di Milano

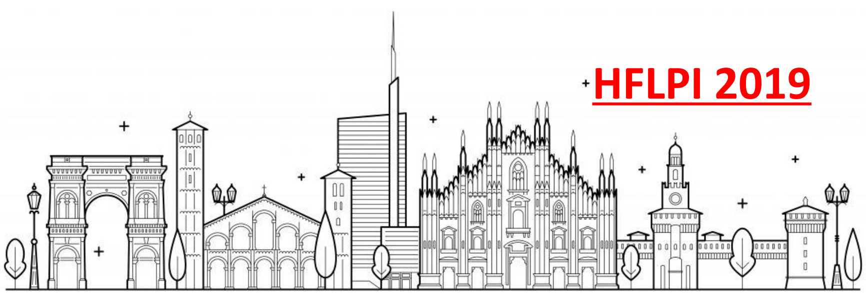
EPS 2019, Milano, 08/07/2019

Outline

- The **ERC ENSURE project** @Nanolab, Politecnico di Milano
  - Theoretical and experimental study of laser-plasma based ion sources
  - Applications in material and nuclear fields
- Enhancing laser-plasma coupling: **nanostructured near-critical plasmas**
- **Target fabrication** for laser-driven ion accelerators
  - Double-layer target concept & production via PLD/HiPIMS
- **Laser-ion acceleration experiments** with double-layer targets
- Theoretical study of **selected applications**
  - Ion Beam Analysis
  - Neutron & radioisotope production
- **Conclusions**

POLITECNICO
MILANO 1863

- Largest university of engineering, architecture, design in Italy
- ~ 40000 students, ~1400 academic staff, 900 PhDs
- 32 BSc, 34 MSc, 18 PhD programmes



HFLPI 2019

EPS DPP satellite workshop on
High-Field Laser-Plasma Interaction
July 13, 2019 Politecnico di Milano, Italy

www.hflpi.polimi.it

ENSURE

Exploring the **N**ew **S**cience and engineering unveiled by **U**ltraintense ultrashort **R**adiation interaction with matt**E**r

POLITECNICO MILANO 1863

DIPARTIMENTO DI ENERGIA

ERC-2014-CoG No.647554

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

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

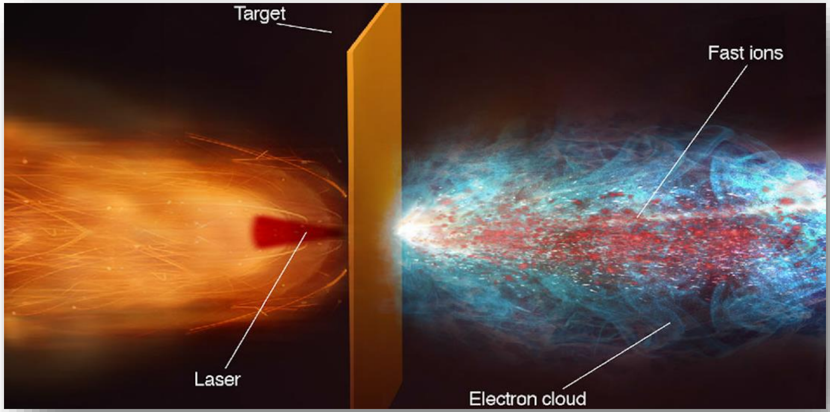
Hosted @ NanoLab, Department of Energy, Politecnico di Milano

Principal investigator:
Matteo Passoni

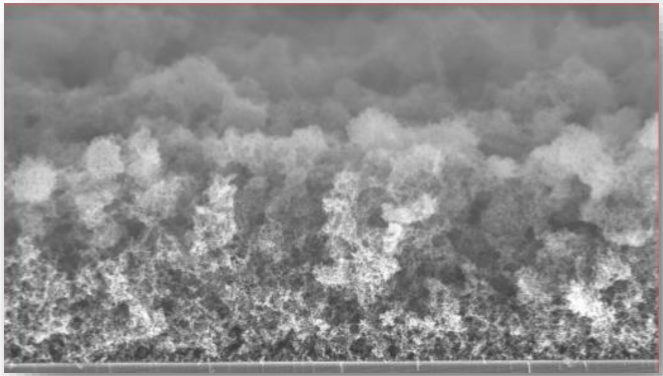
Team: PI, 1 Associate Professor, 1 Assistant Professor, 2 Post-Docs, 3 PhDs + master students and support from NanoLab people

www.ensure.polimi.it

ENSURE: Main fields of research



Theoretical & experimental investigation of **laser-plasma based ion acceleration**



PVD-plasma based advanced materials production & characterization
(low-density foams & multilayer targets) for laser-plasma interaction experiments

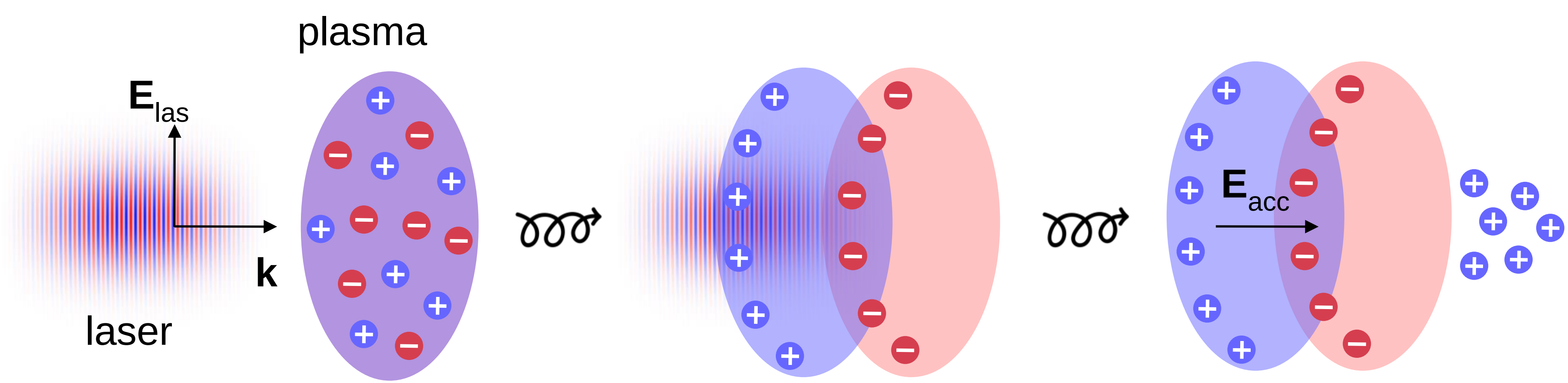
Application of laser-driven ion acceleration in **material** & **nuclear fields**
(Laser-driven Ion Beam Analysis,
Compact neutron & radioisotope sources)

Plasmas as charged particle accelerators

laser + plasma

strong charge separation

charged particle acceleration



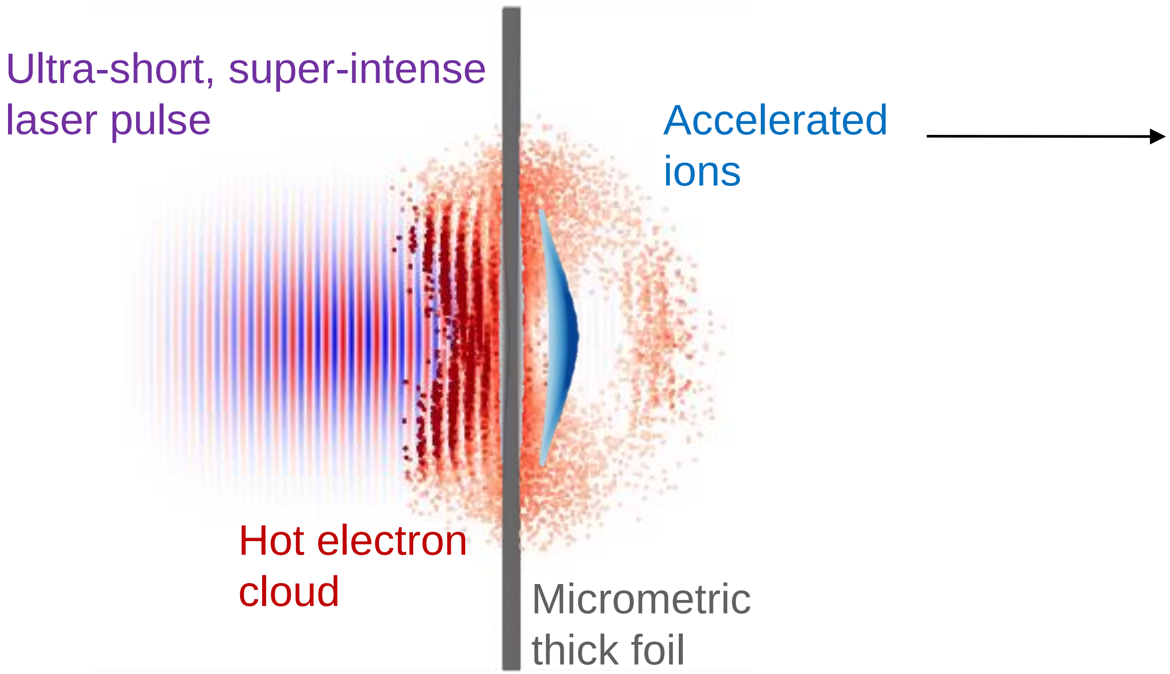
$\mathbf{E}_{las}$
- transverse
- oscillating

laser-plasma interaction →

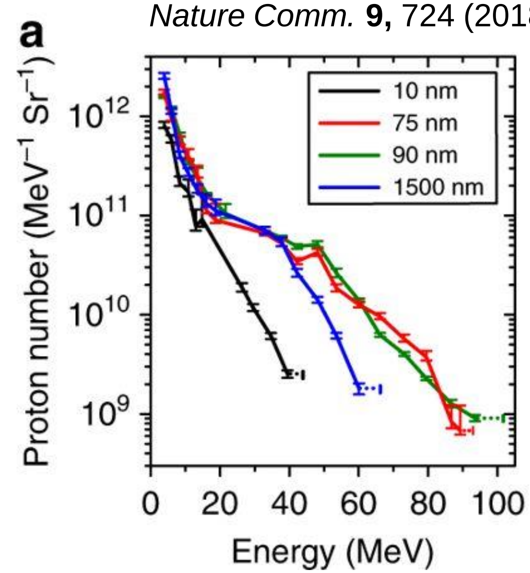
$\mathbf{E}_{acc}$
- longitudinal
- quasi-static

$\mathbf{E}_{las} \sim \mathbf{E}_{acc} > 0.1$ MV/µm

Laser-plasma acceleration of ions



From A. Higginson et al., *Nature Comm.* **9,** 724 (2018)



A. Macchi at al., *Rev. Mod. Phys.* **85**, 751 (2013)
H. Daido et al., *Rep. Prog. Phys.* **75**, 056401 (2012)

Interesting for plasma physics:

- **fundamental physics**: explore novel regimes → PW
- **applications**: employ the ions for a specific purpose → HRR

Challenge: **control** and tune the **laser-plasma coupling**

Near-critical regime for laser-driven acceleration

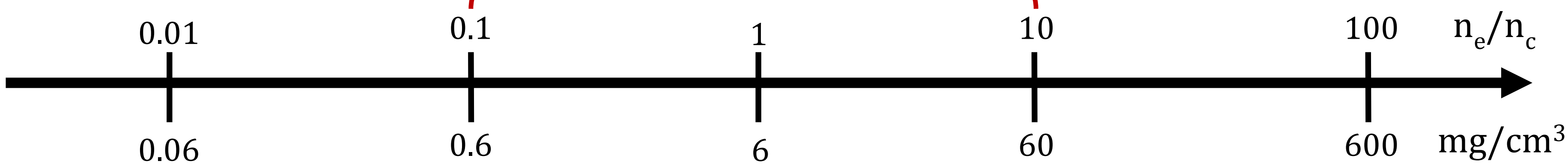
I_{laser}=10^{20} W/cm^2 ⟶ $\mathbf{E}_{laser}$ = 3 x 10^{11} V/m = 50 X $\mathbf{E}_{atomic}$ ⟶ Full ionization ⟶ Plasma!

Plasma critical density: $$n_c = \frac{\pi\, m_e c^2}{e\, \lambda^2}$$ $n_c \approx 6\ \mathrm{mg/cm^3}$ (@ λ=800 nm)

$n \approx n_c$ near critical plasma
strong laser-plasma coupling

$n \ll n_c$ underdense plasma
little laser absorption

$n \gg n_c$ overdense plasma
most of laser is reflected



GAS

SOLIDS

Near-critical materials:

- Very dense gas/criogenic jets
- Carbon nanotubes foams
- Carbon nanoparticle foams

Near-critical regime for laser-driven acceleration

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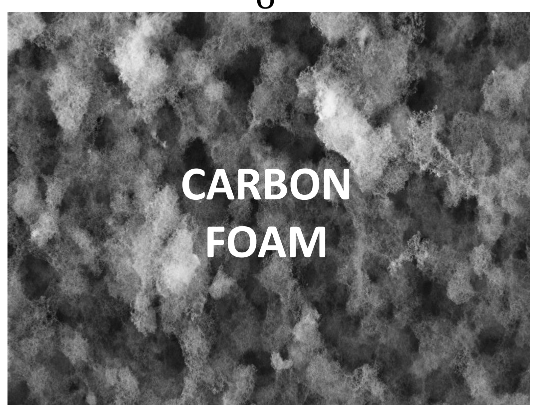
most of laser is reflected

n_e/n_c	0.01	0.1	1	10	100
mg/cm^3	0.06	0.6	6	60	600

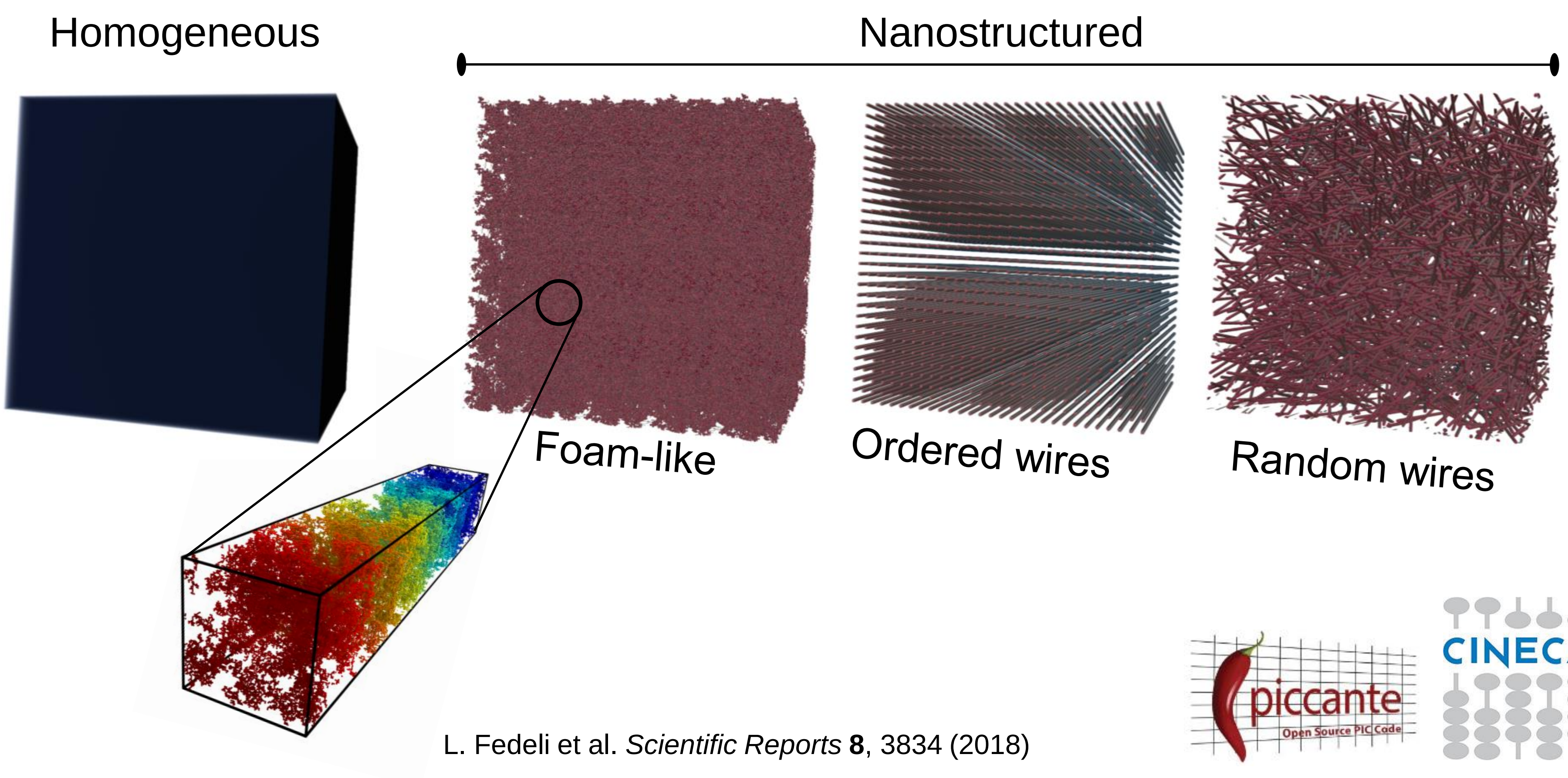
GAS ... **SOLIDS**



Role of plasma nanostructure
in the laser-plasma coupling
poorly investigated & understood

Particle-In-Cell (PIC) simulations to study laser-plasma interaction

Inclusion of the plasma **nanostructure & morphology** to properly model physical processes



L. Fedeli et al. *Scientific Reports* **8**, 3834 (2018)

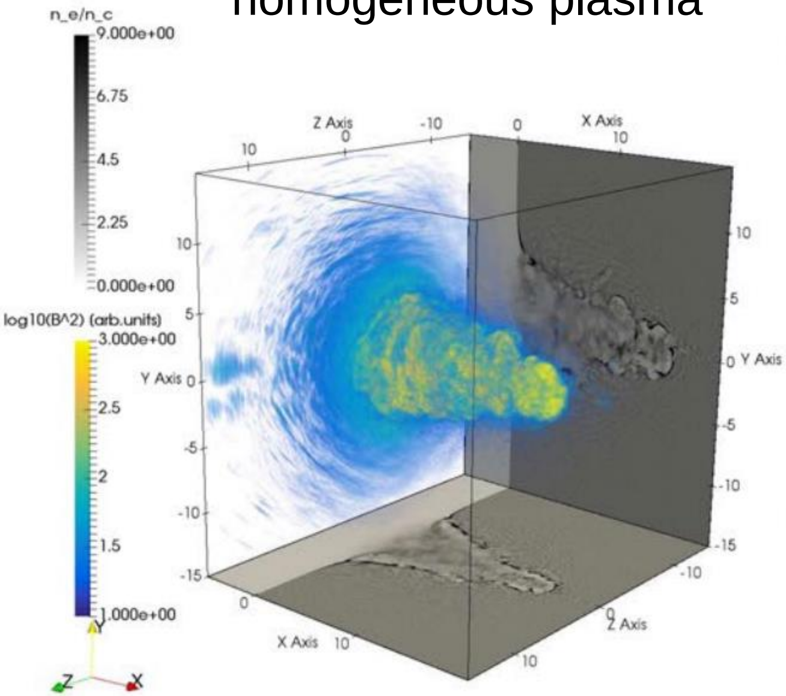
piccante Open Source PIC Code

CINECA

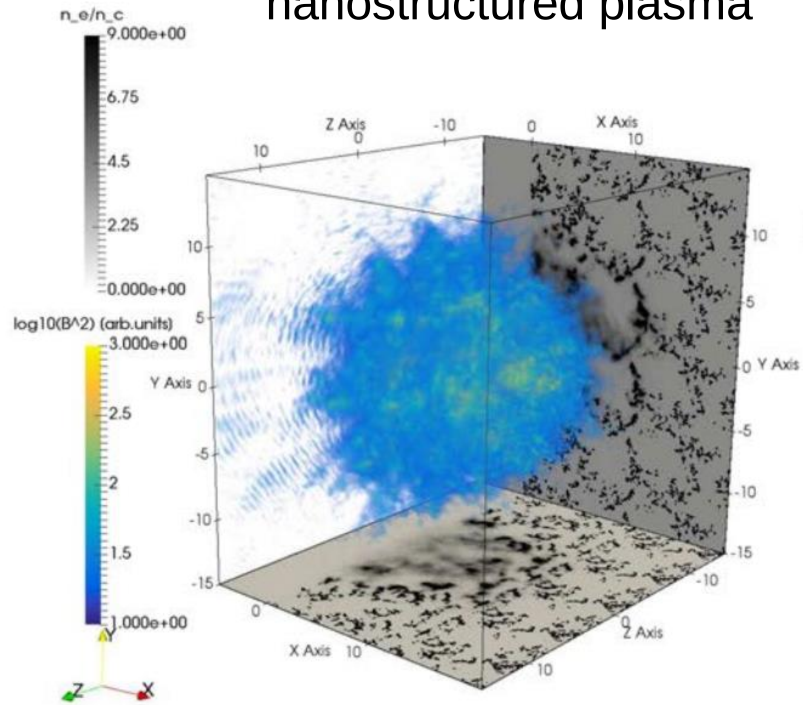
3D PIC simulations of laser-plasma interaction with nanostructured plasmas

- Realistic nanostructure representative of the foam growth process
- Same average electron density ~ 3 n_c for fair comparisons

homogeneous plasma

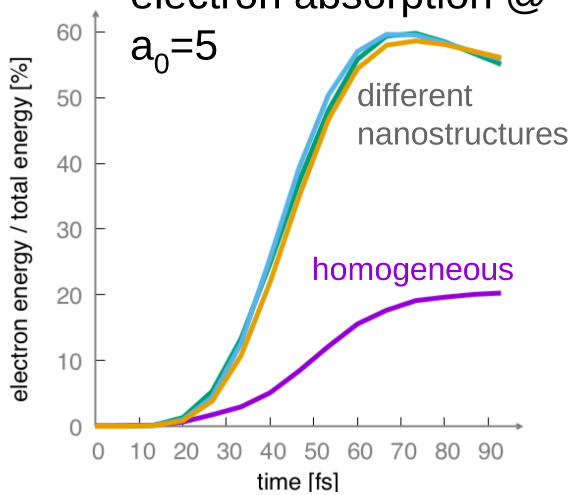


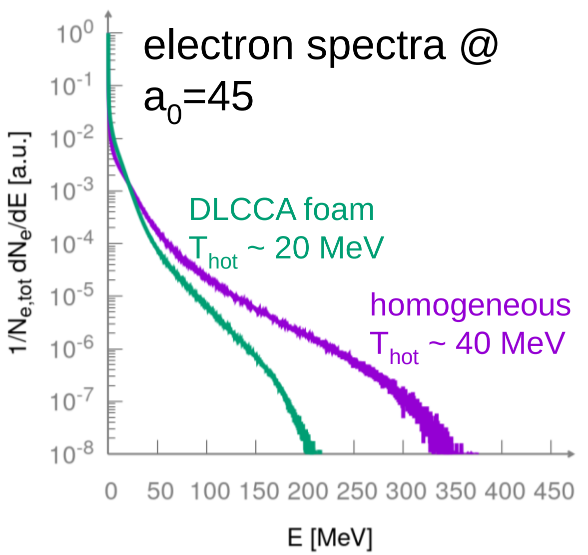
nanostructured plasma

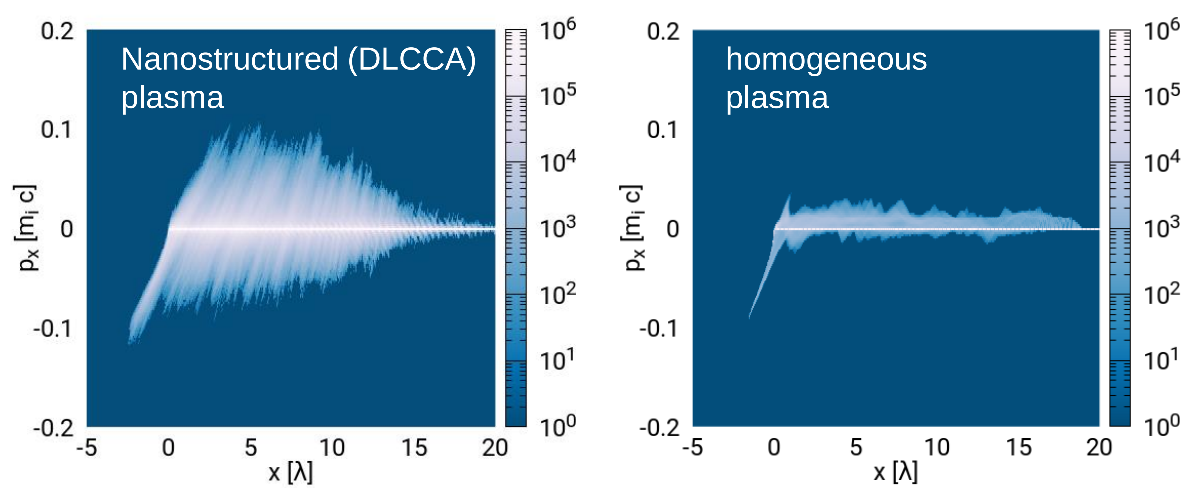


a_0 = 45, normal incidence, P-pol

3D PIC simulations show that it is important to include the plasma nanostructure







Plasma nanostructure effects:

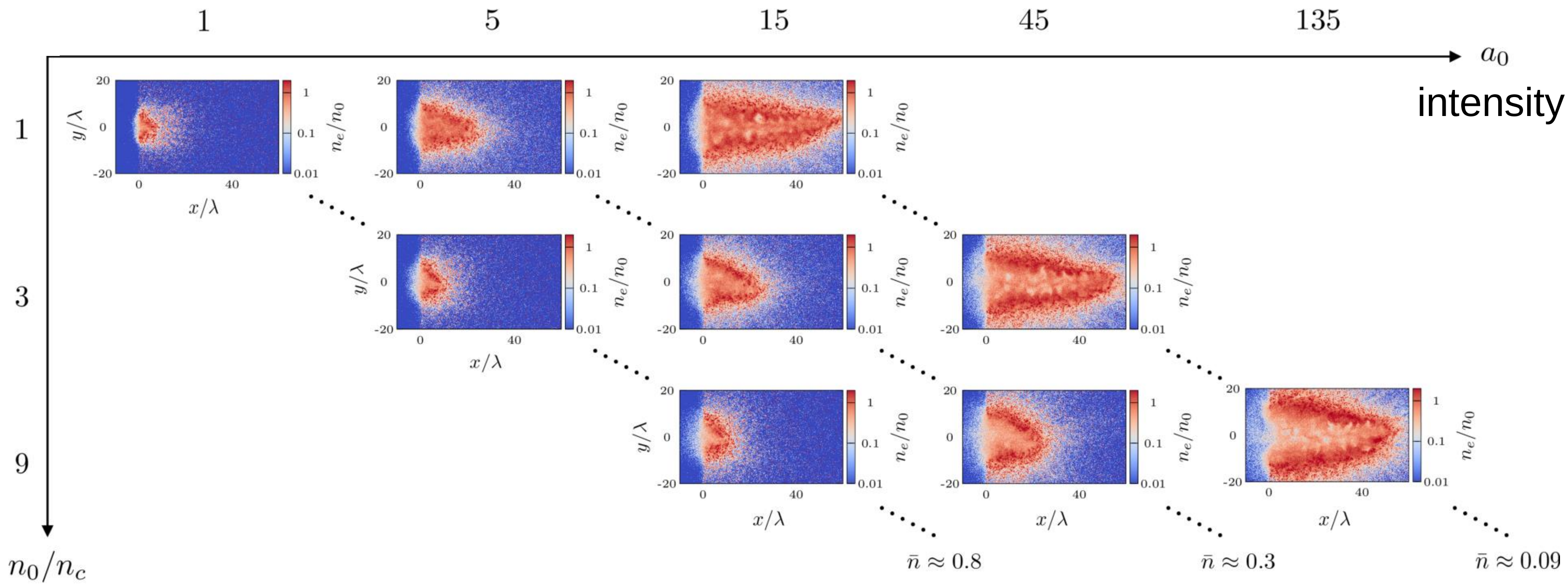
- stronger electron absorption
- much stronger ion absorption
- nanoparticles “explosion”
- higher hot electron T, if high enough a_0
- [...]

→ for a good description, one **cannot disregard the nanostructure – if any**

see A. Formenti’s talk @HFLPI, July 13 2019

2D PIC parametric simulations of laser-plasma interaction with nanostructured plasmas

- The nanostructure is a collection of “nanospheres” randomly arranged in space
- Wide range of regimes, but inherent limitations



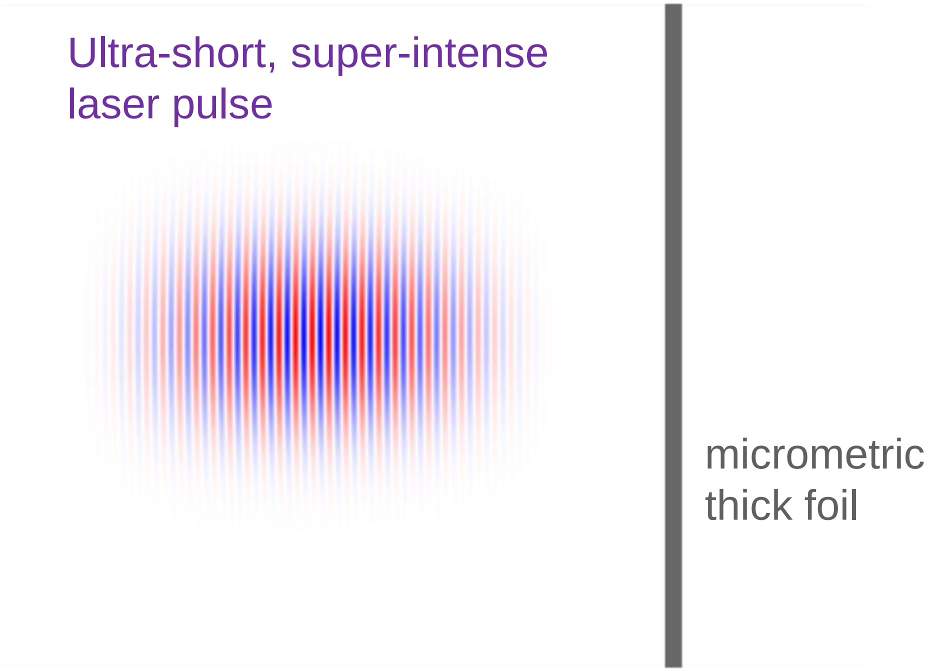
average density

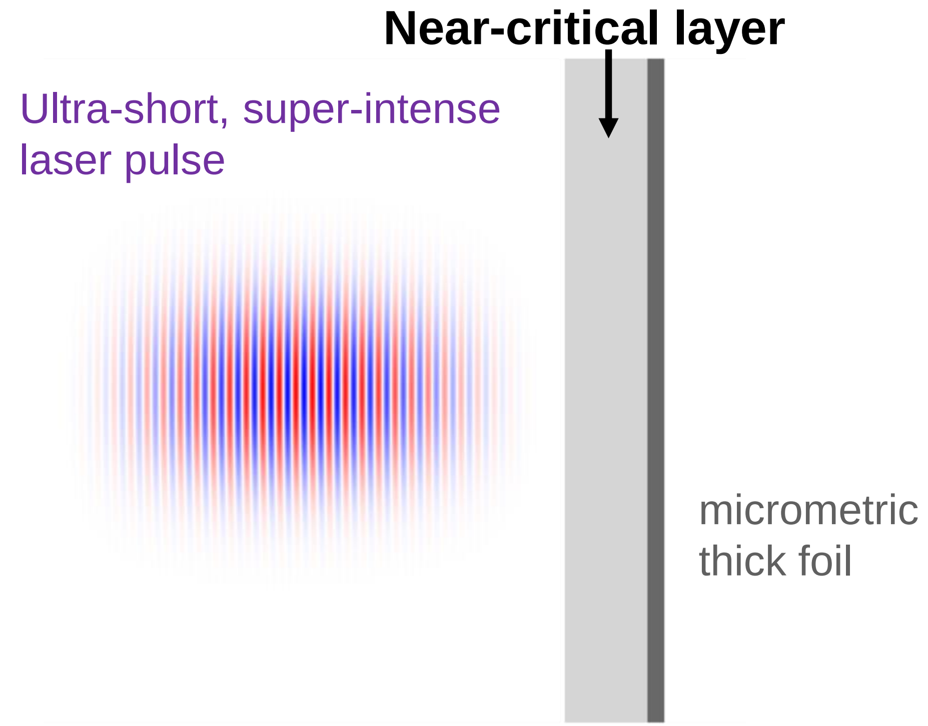
L. Fedeli et al., *Eur. Phys. J. D* **71**, 202 (2017)

$$\bar{n} = \frac{n_e/n_c}{\sqrt{1 + a_0^2/2}}$$

Laser-ion acceleration: Target is the key

I. Prencipe et al. *High Power Laser Sci.* **5**, e17 (2017)





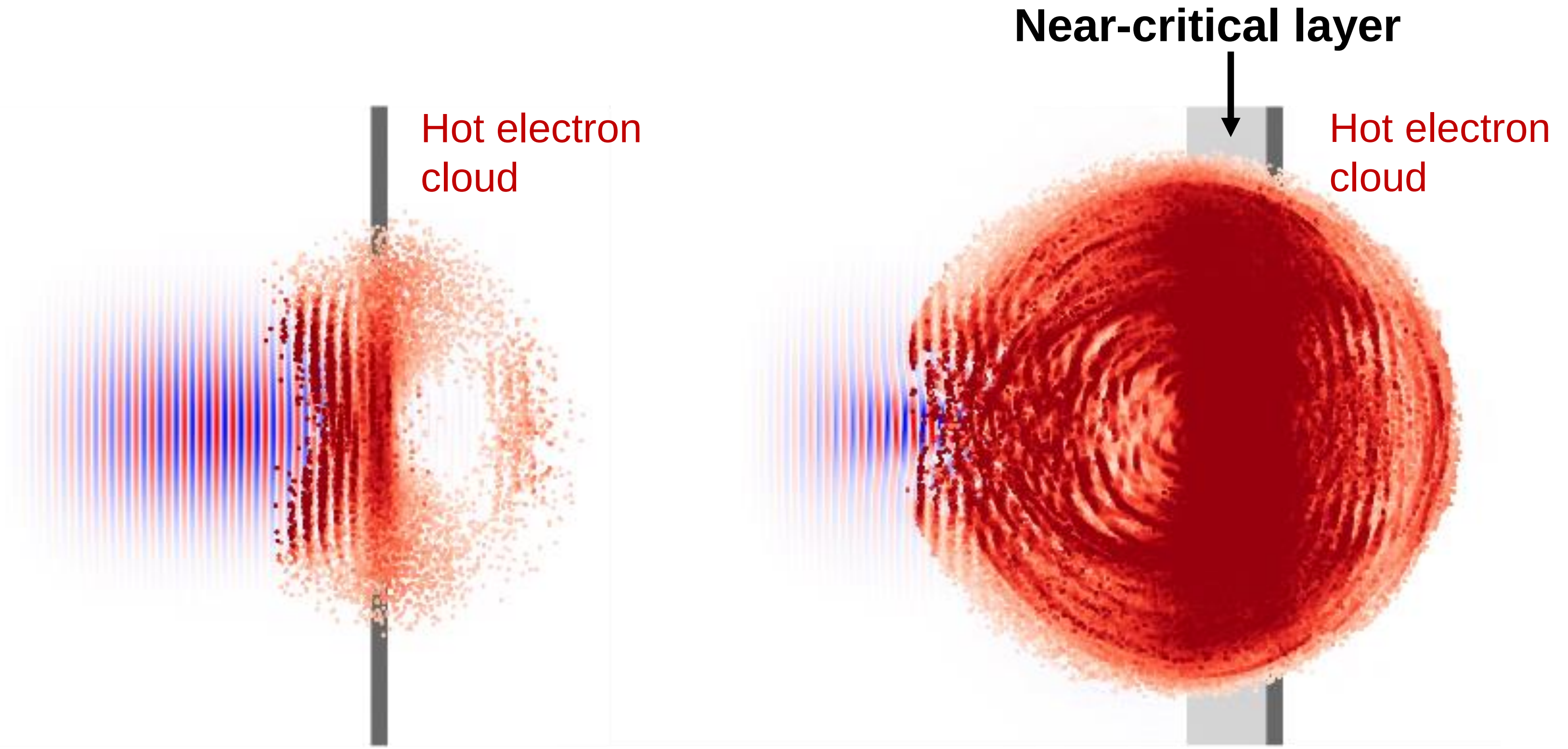
Target Normal Sheath Acceleration (TNSA)

Enhanced TNSA

- Near-critical layer onto a μm-thick foil

M. Passoni et al. *Phys Rev Acc Beams* **19**, 061301 (2016)

Target is the key

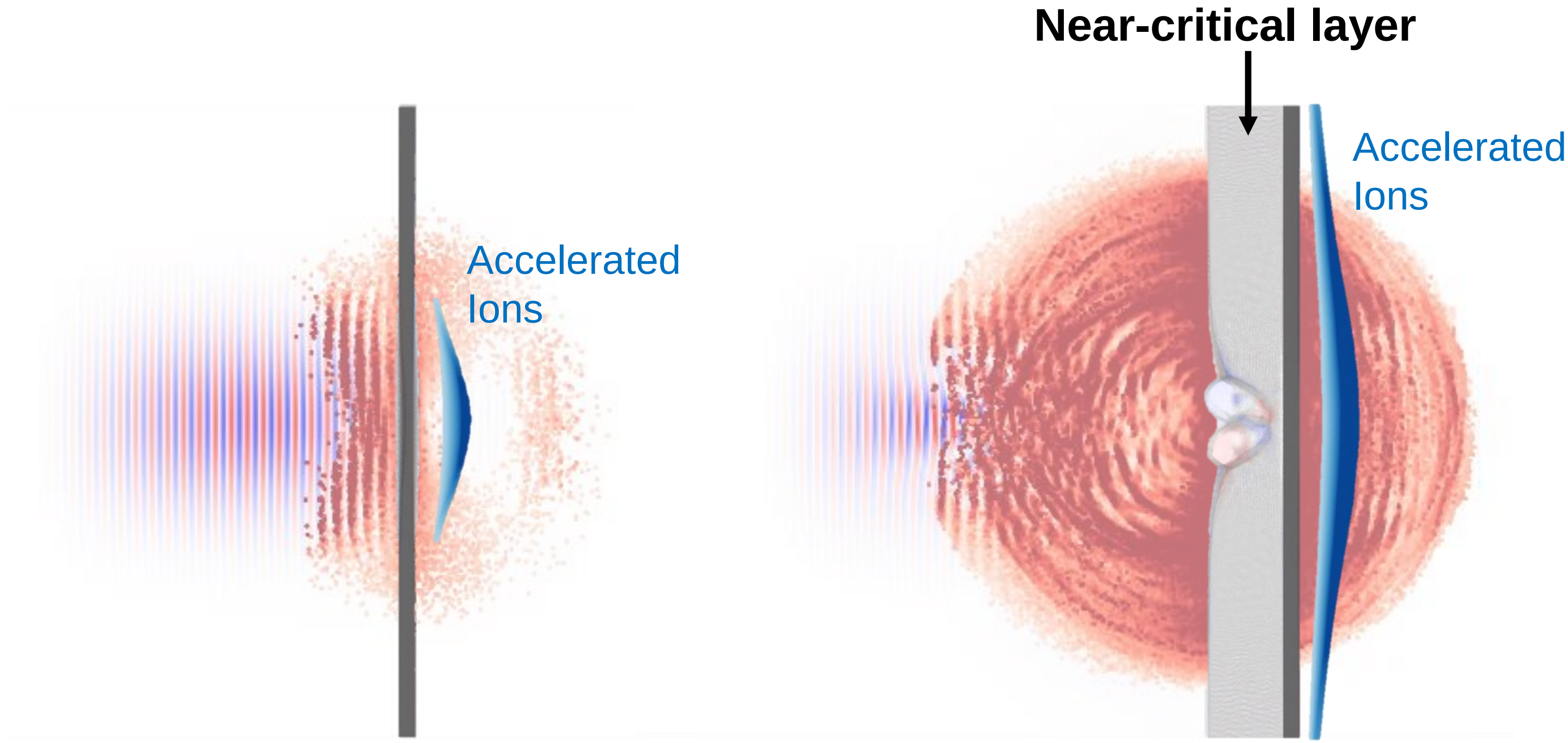


Conventional TNSA **Enhanced TNSA**

- ❑ Near-critical layer onto a μm-thick foil
- ❑ More and hotter relativistic electrons

M. Passoni et al. *Phys Rev Acc Beams* **19**, 061301 (2016)

Target is the key



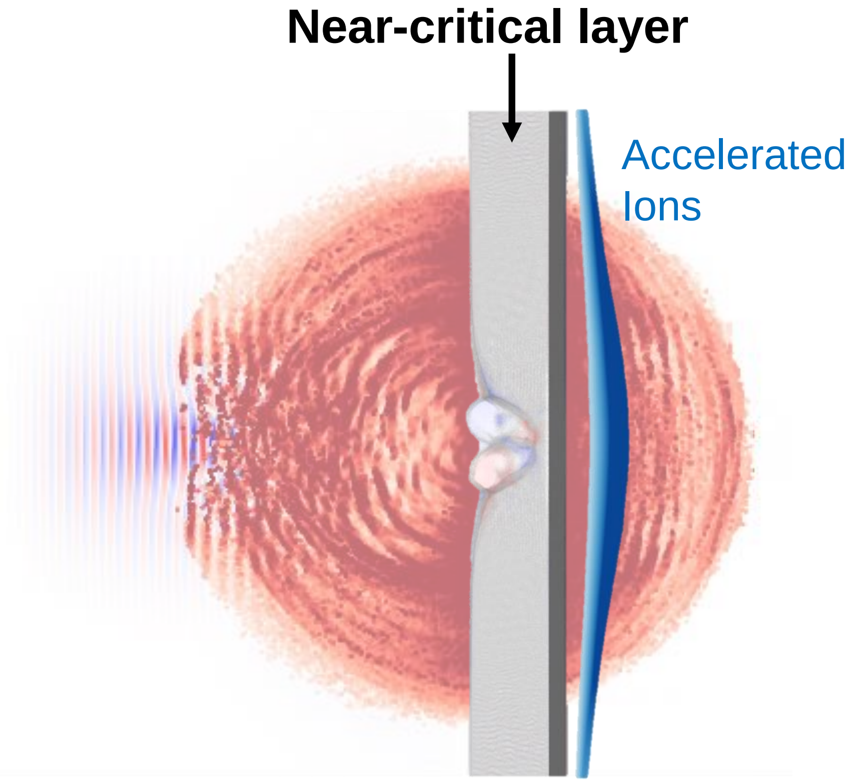
Conventional TNSA | **Enhanced TNSA**

The target is the key!

M. Passoni et al. *Phys Rev Acc Beams* **19**, 061301 (2016)

- ❑ Near-critical layer onto a μm-thick foil
- ❑ More and hotter relativistic electrons
- ❑ **More ions at higher energy**

Production and use of targets for laser-ion sources



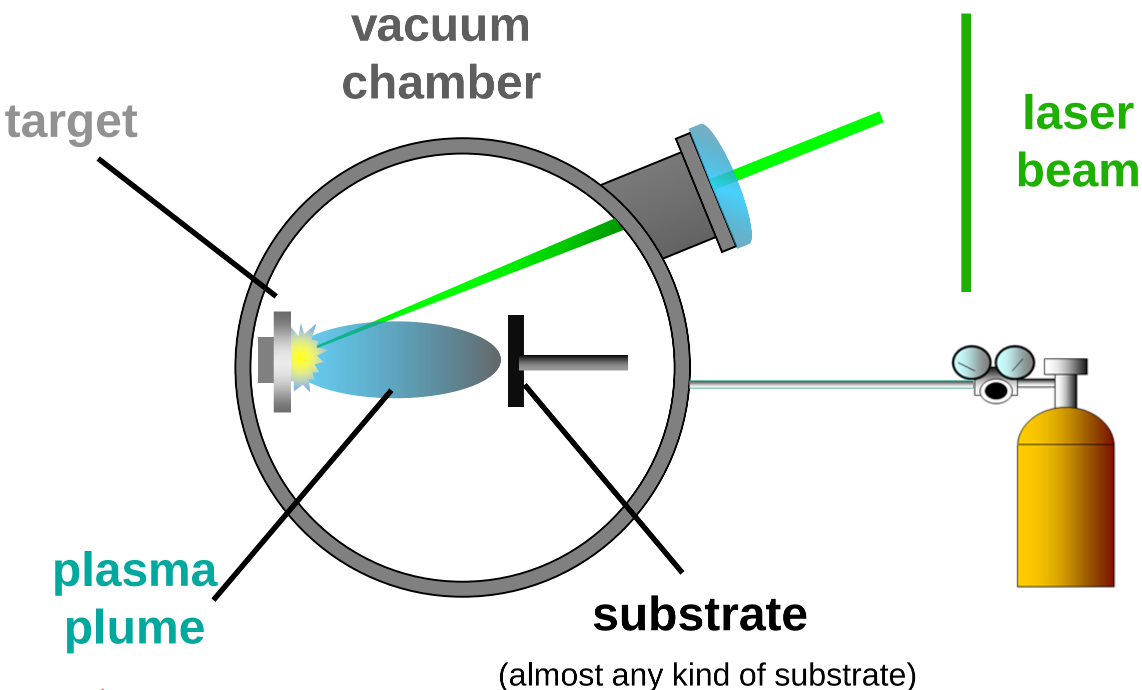
Enhanced TNSA

The target is the key!

TARG4 Workshop, June 10-12 2019
Politecnico di Milano, www.targ4.polimi.it

- **Production of multi-layer targets**
  - Production of near-critical foams
    ↓
    Pulsed Laser Deposition
  - Production of solid layers
    ↓
    High Power Impulse Magnetron Sputtering
- **Laser-ion acceleration experiments**
  ↓
  Dedicated experimental campaigns
- **Applications of compact laser-ion sources in materials and nuclear fields**

How to produce foams: Pulsed Laser Deposition (PLD)

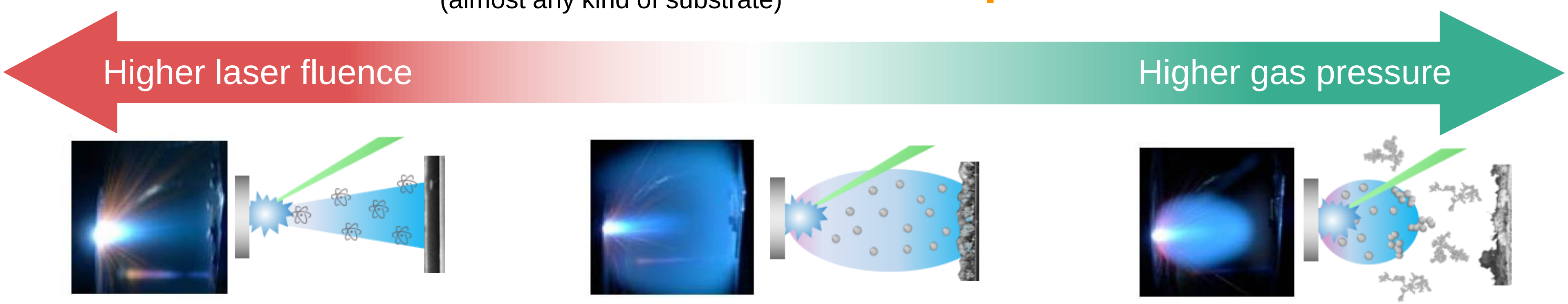


laser beam

	ns-PLD	fs-PLD
Energy	1 J	5 mJ
Rep. rate	10 Hz	1 kHz
Pulse duration	**7 ns**	**80 fs**

Different interaction regimes!

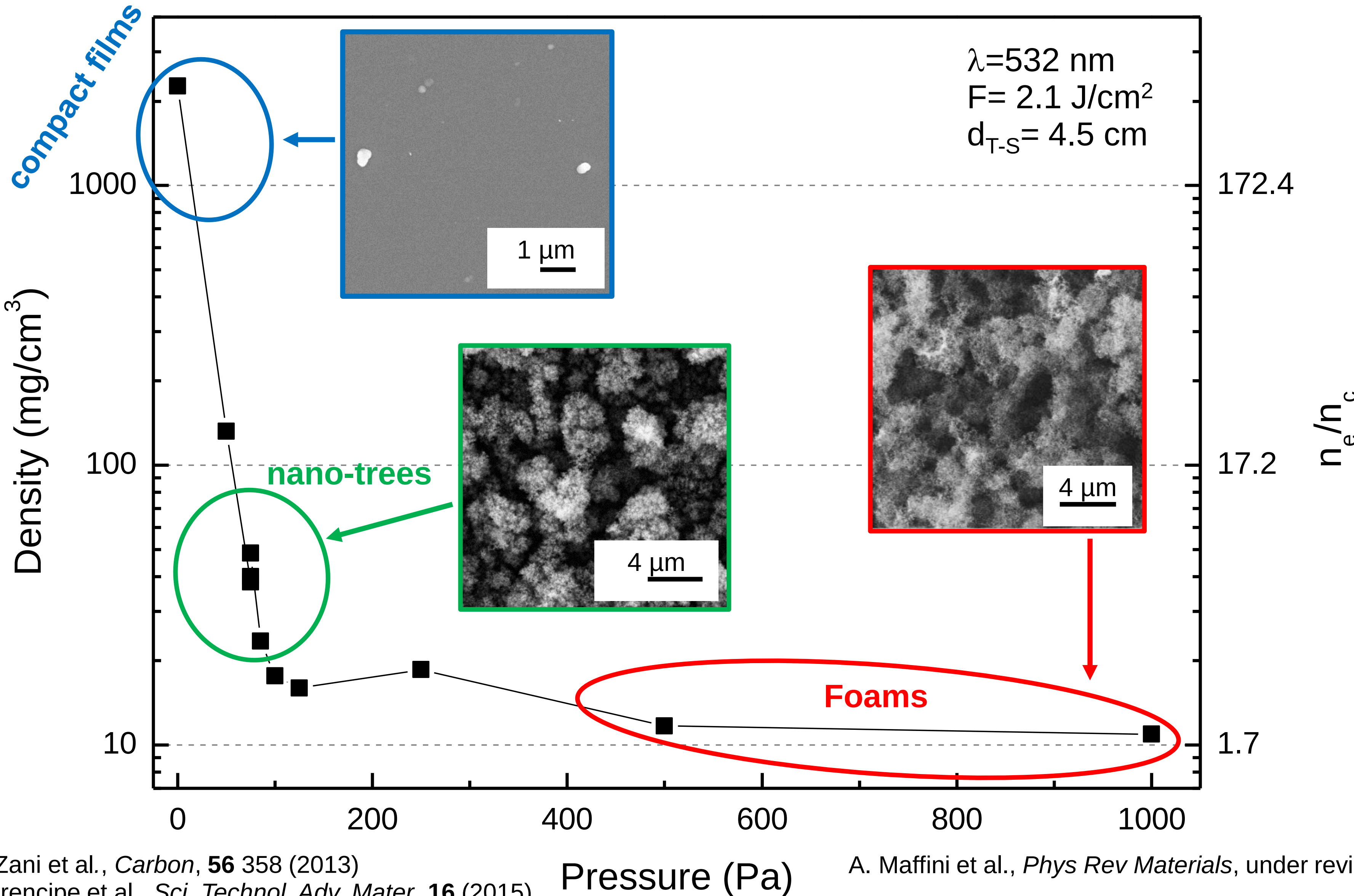
background gas



«atom by atom» deposition

nanoparticles aggregates deposition

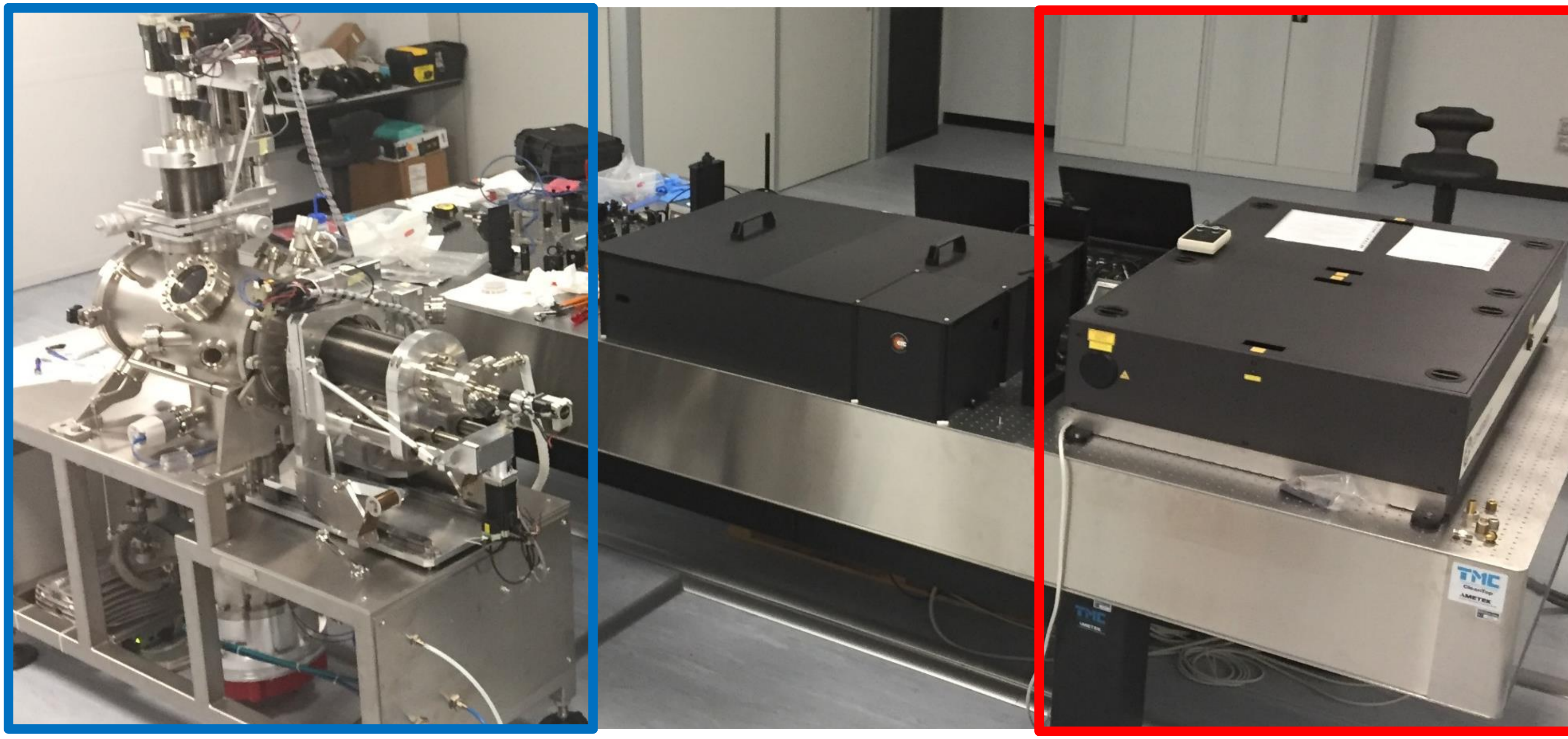
How to produce carbon foams with ns-PLD



A. Zani et al., *Carbon*, **56** 358 (2013)
I. Prencipe et al., *Sci. Technol. Adv. Mater*. **16** (2015)

A. Maffini et al., *Phys Rev Materials*, under review

New experimental facilities @Nanolab: fs-PLD



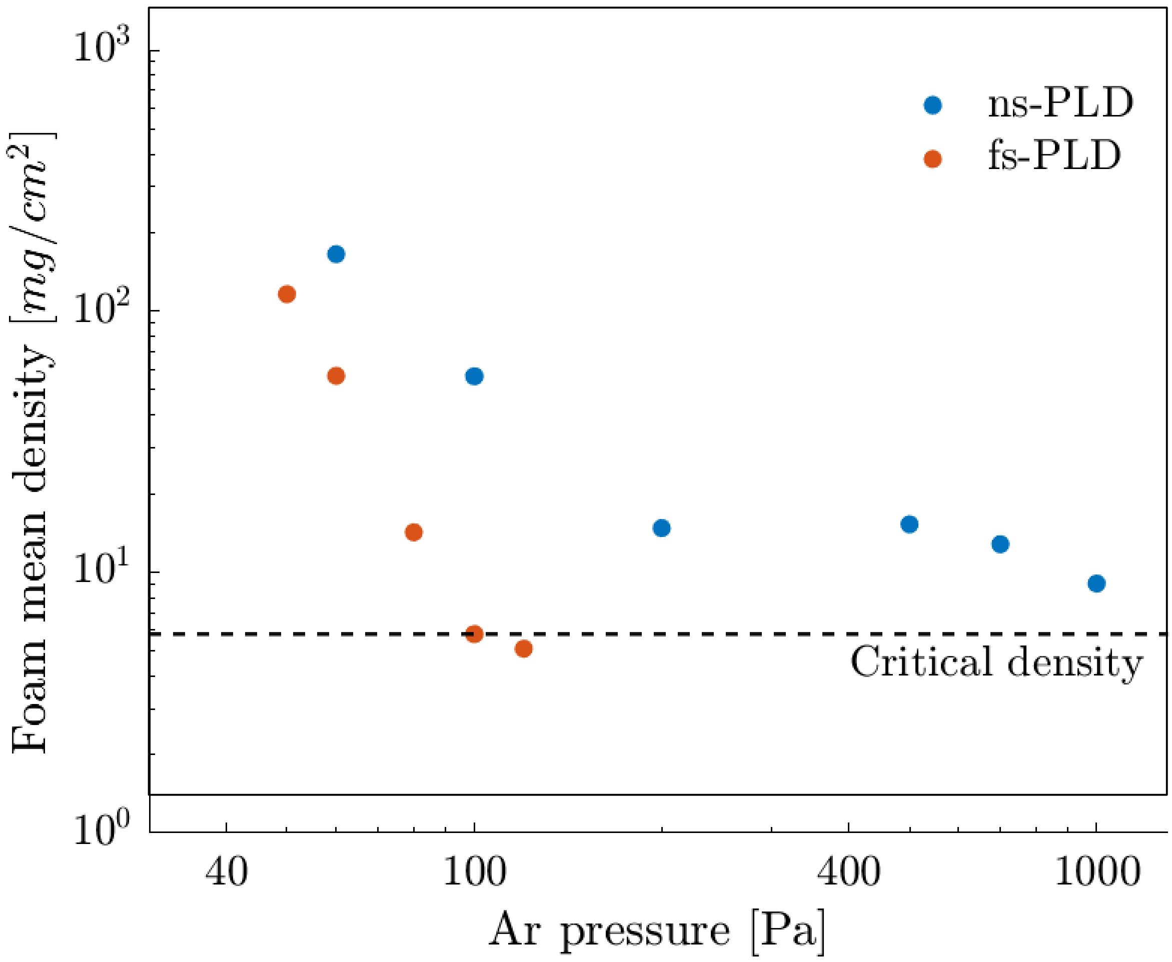
fs-PLD interaction chamber

- ❑ PLD mode + Laser processing
- ❑ up to 4 targets
- ❑ Upstream + downstream pressure control
- ❑ Fast substrate heater
- ❑ Fully automated software

Coherent Astrella ™

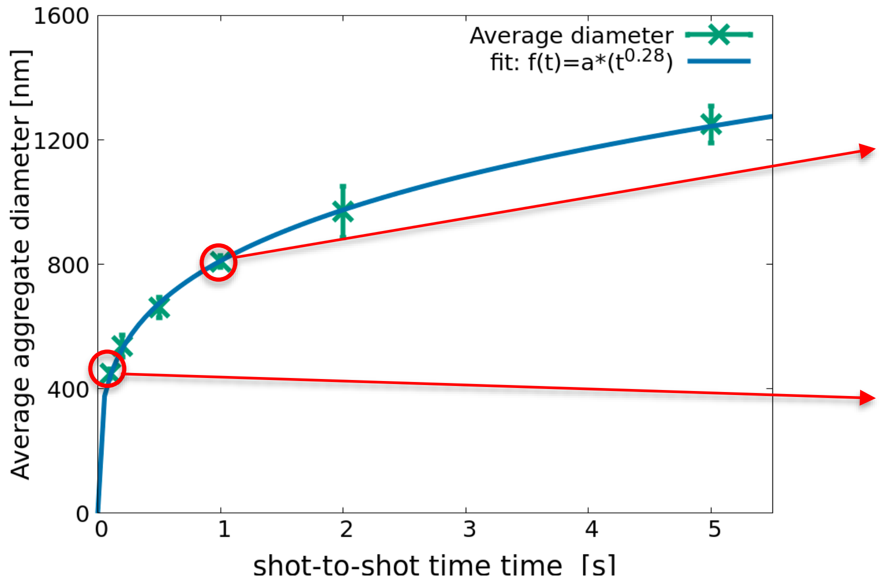
- ❑ Ti:Shappire λ=800 nm
- ❑ Ep > **5 mJ**
- ❑ Pulse duration **< 100 fs**
- ❑ Peak Power > 50 GW
- ❑ Rep Rate = 1000 Hz

fs-PLD opens new perspectives toward near-critical nanomaterials

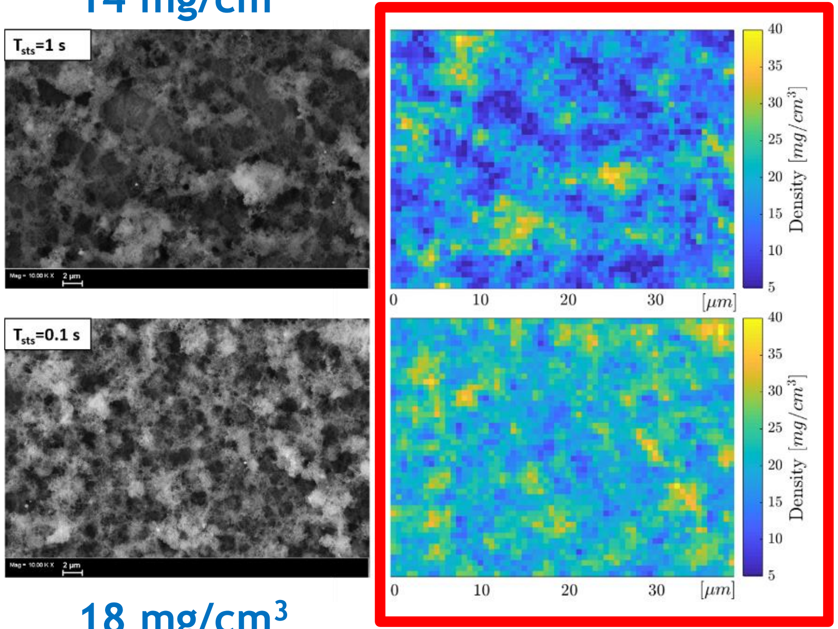


A "snowfall model" to describe nanofoam growth

1) Nanoparticles generated at the beginning of plume expansion
2) Nanoparticles coalesce into larger aggregates...
3) ...until the subsequent laser-generated shock wave drives them to substrate
4) **Laser repetition rate emerges as a new free parameter!**



14 mg/cm^3



18 mg/cm^3

EDXS density map to evaluate foam uniformity

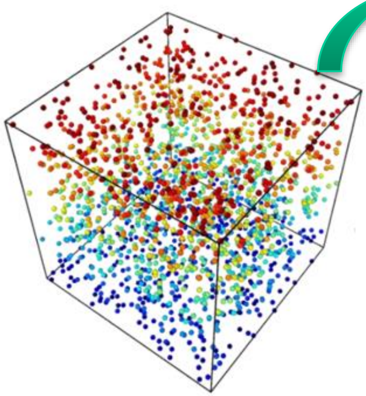
A. Pazzaglia et al., *Materials Characterization* **153**, 92 (2019)

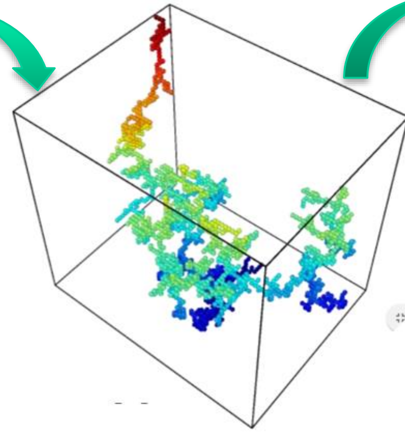
A. Maffini et al., *Phys. Rev. Materials,* under review

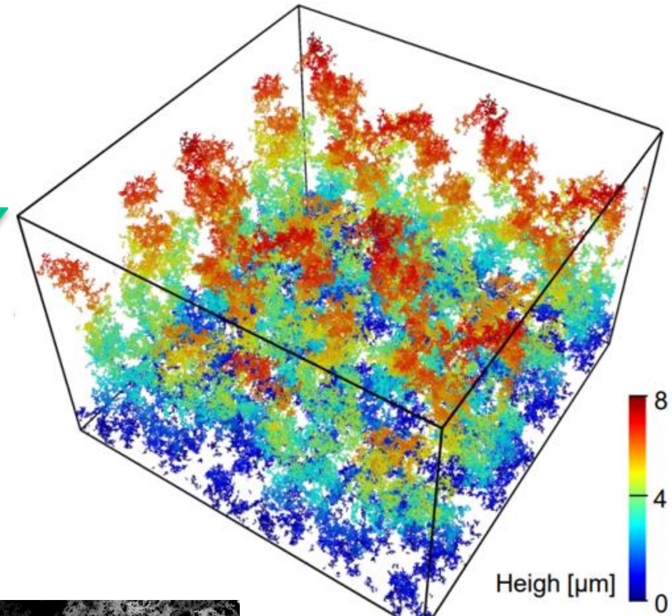
Aggregation model to study the foam growth

Diffusion-Limited Cluster-Cluster Aggregation (DLCCA):

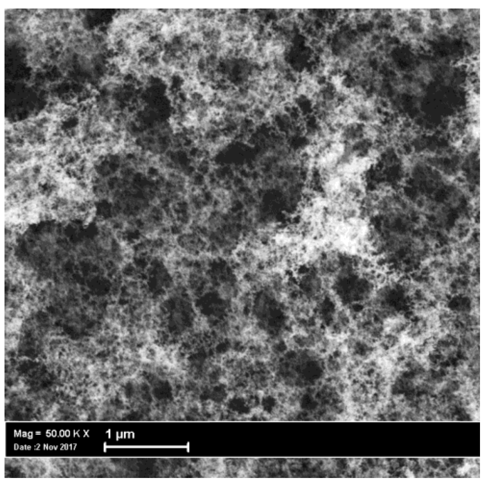
1) Brownian motion of particles
2) Particle aggregation in clusters by irreversible sticking
3) Clusters deposition on substrate

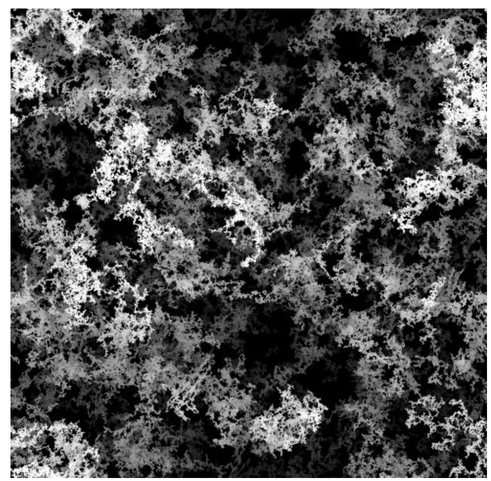






Real Foam

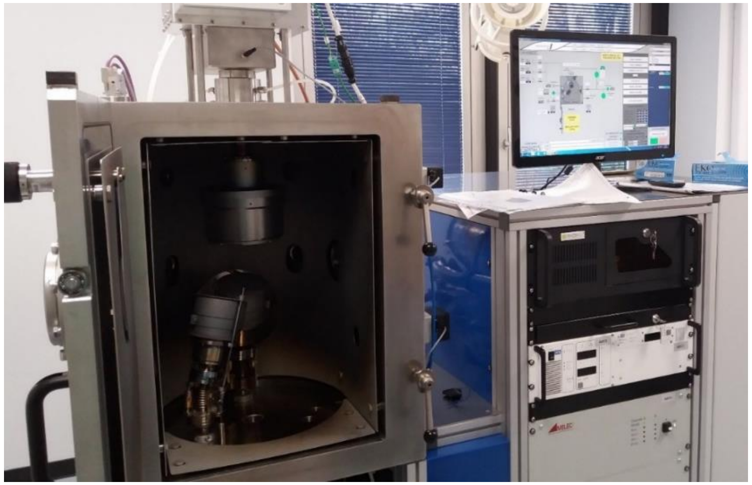




Simulated Foam

Input for realistic 3D-PIC simulations!

New experimental facilities @Nanolab: HiPIMS

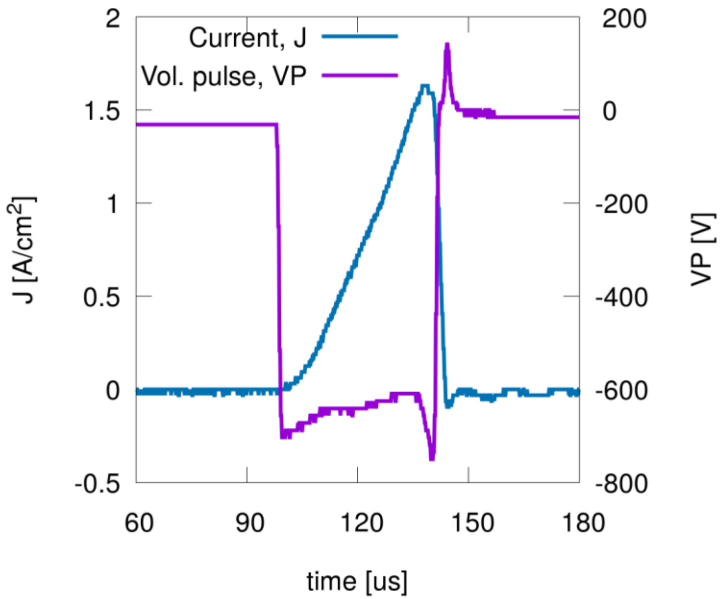


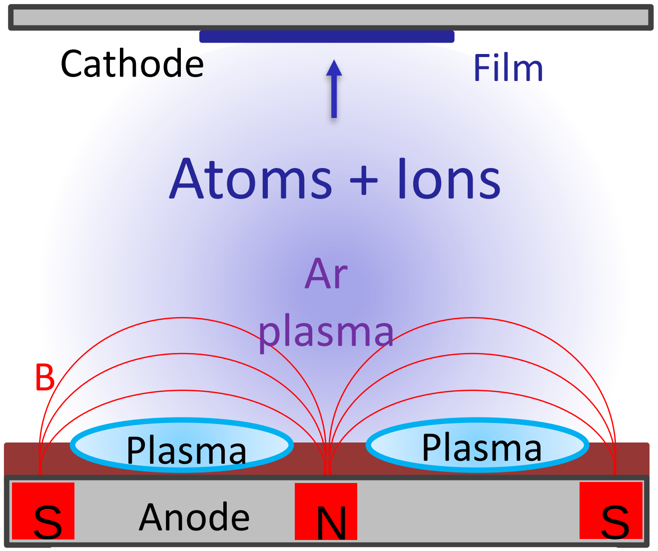
High Power Impulse Magnetron Sputtering (HiPIMS)

Pulsed High Power Voltage (50 us, 800 V)

↓

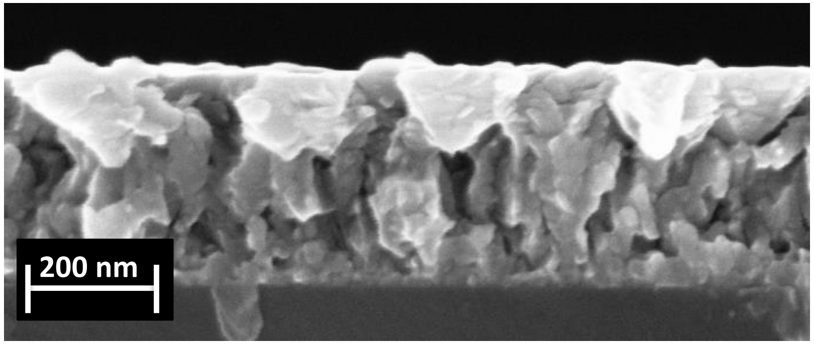
- ❑ Peak power density = 10^3 W/cm²
- ❑ Peak current density = 1 – 5 A/cm²



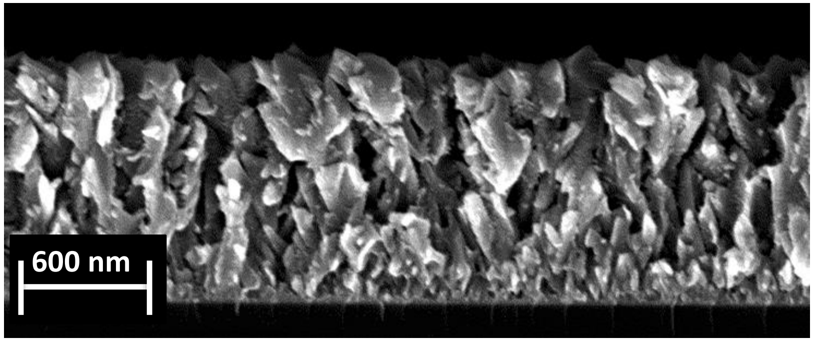


Compact solid layers in HiPIMS mode!

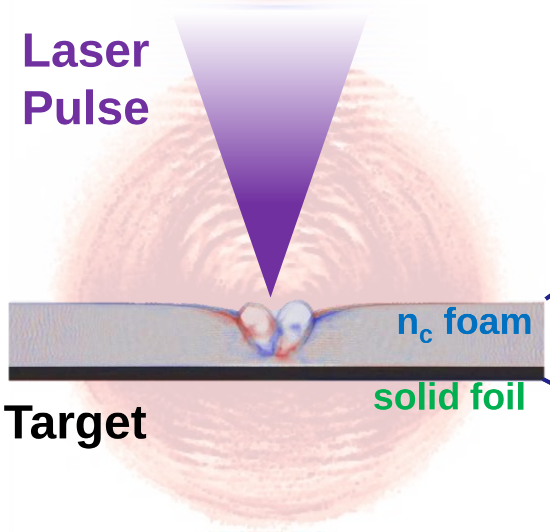
HiPIMS



DCMS



Combined PLD & HiPIMS deposition techniques to produce the desired near-critical double-layer target



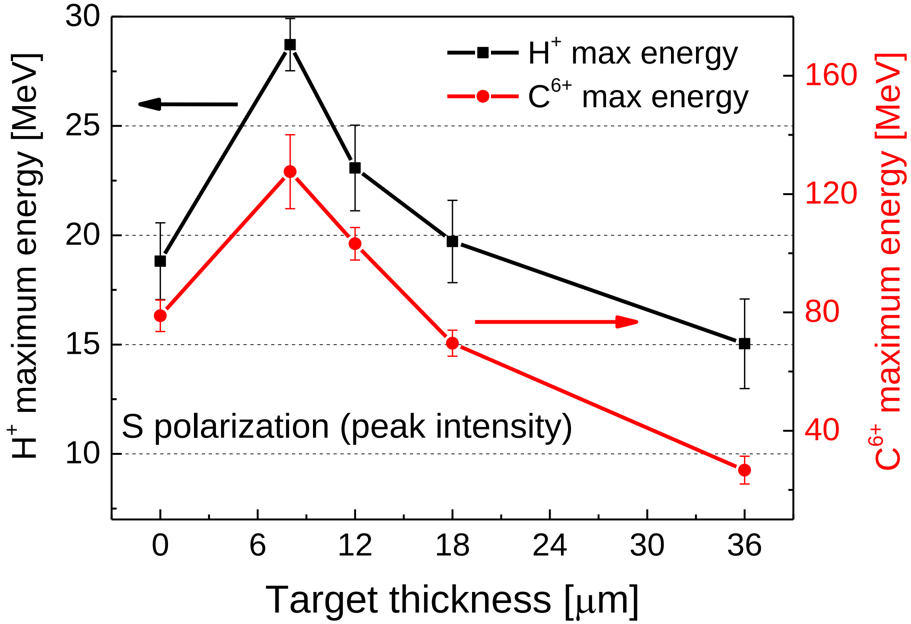
D. Vavassori, *MSc thesis in Nuclear Engineering* (2019)

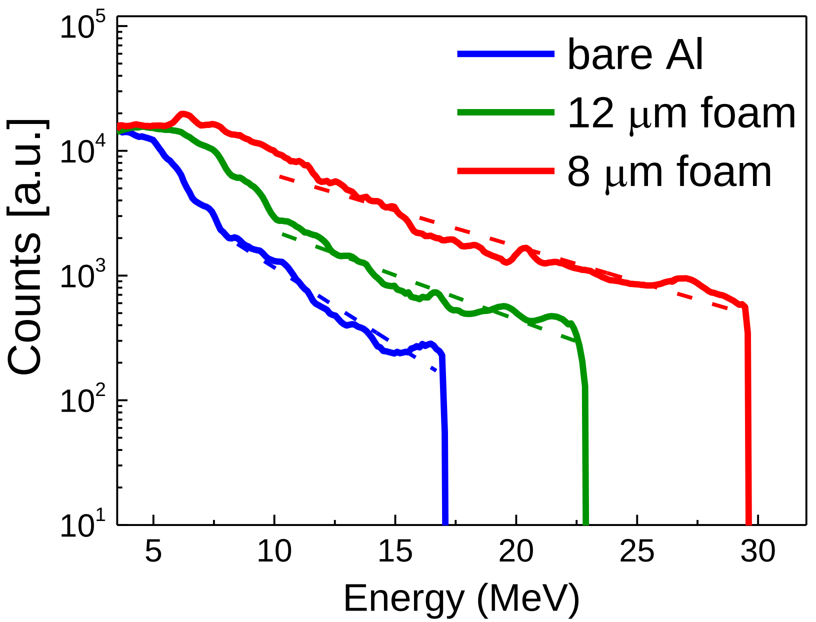
Ion acceleration @PULSER (GIST)

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

Role of target properties (s-pol, ~ 7 J, 3×10^{20} Wcm^{-2}, 30° inc. angle)

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





- There is an **optimum** in near critical layer **thickness**
- **Maximum** proton **energy enhanced** by a factor ~ **1.7**
- **Number** of proton **enhanced** by a factor ~ **7**

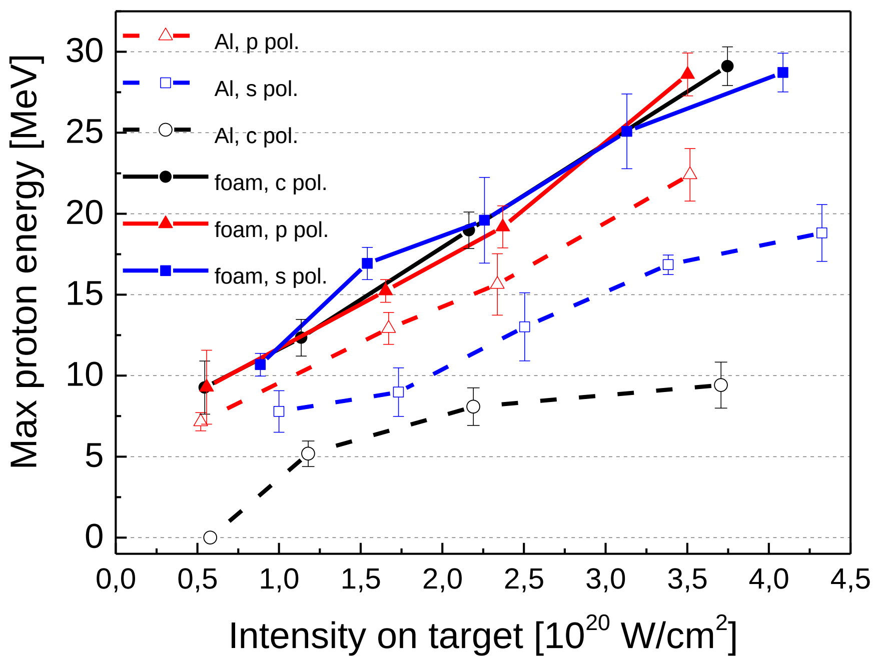
M. Passoni et al., *Phys. Rev. Accel. Beams* **19**, (2016)
I. Prencipe et al., *Plasma Phys. Control. Fus.* **58** (2016)

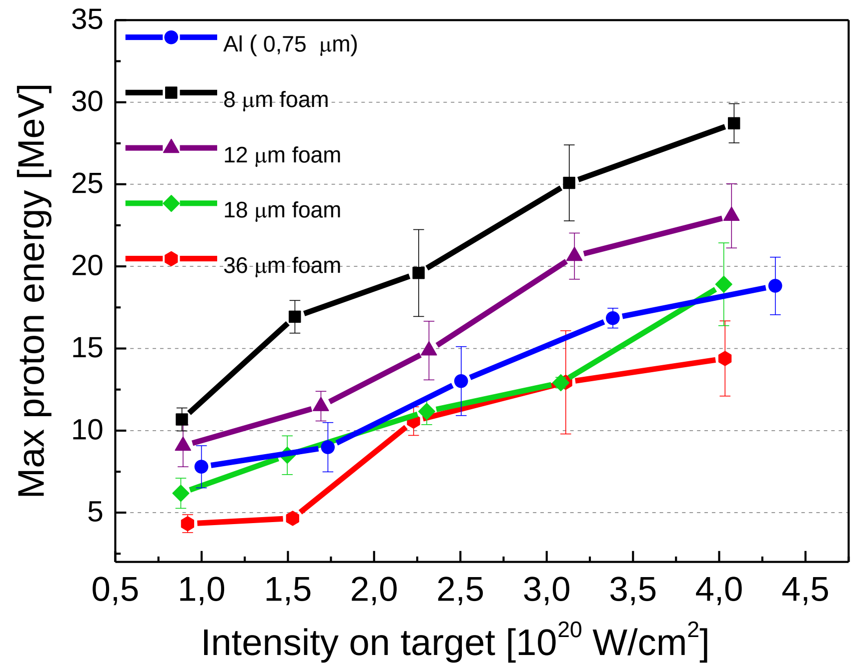
Ion acceleration @PULSER (GIST)

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

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

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





Dependence on **polarization**:

- strong for Al foils
- reduced for foam targets

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

Ion acceleration @DRACO 150 TW

HZDR

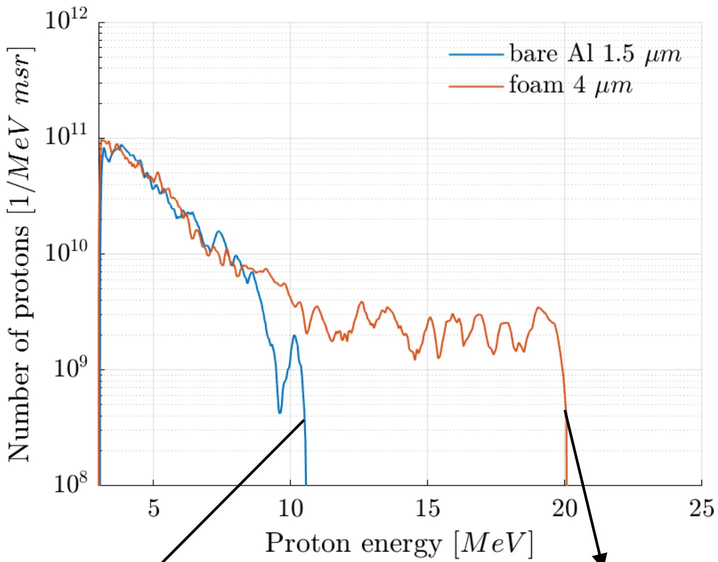
in collaboration with:
I. Prencipe, T. Cowan, U. Schramm et al.

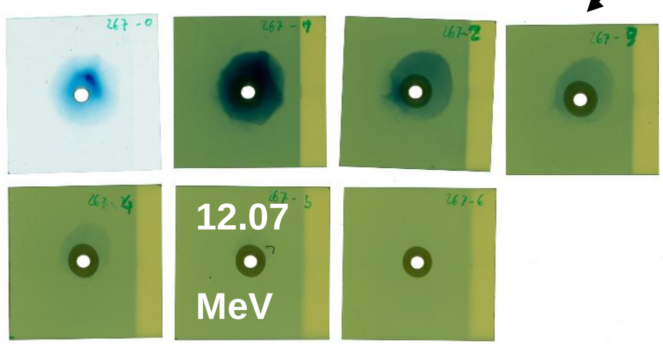
Laser parameters @ Draco (HZDR, Dresden)

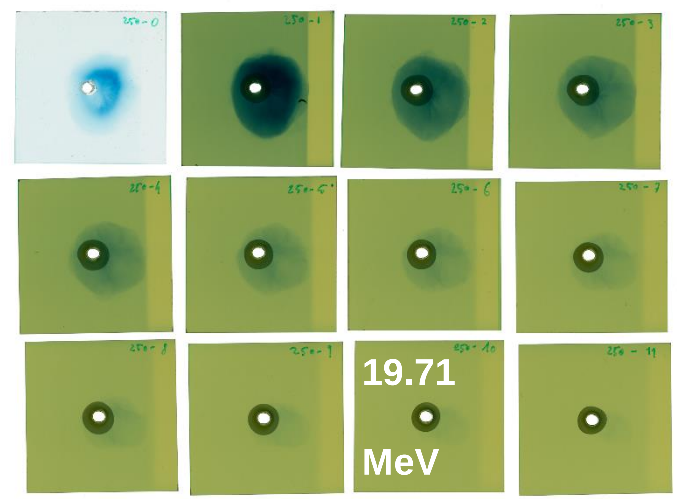
- Energy on target = 2 J
- Intensity = up to 5 x 10^{20} W/cm^2
- Angle of incidence = 2°

Foam PLD parameters

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







- ❑ **Up to 2x energy**
- ❑ **Up to 4x particles**

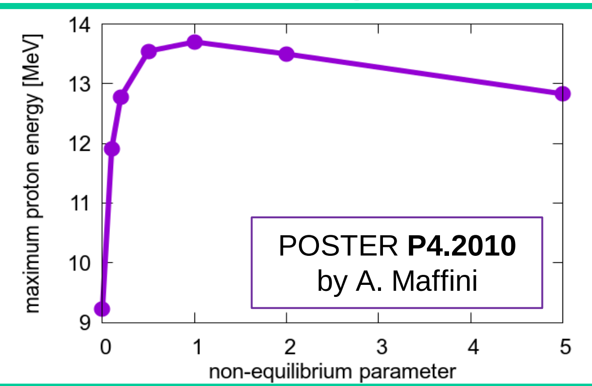
Laser-ion acceleration theoretical modeling

Modeling of laser generated hot electron population

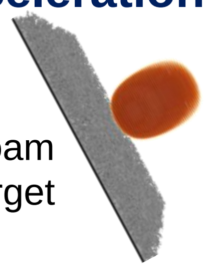
$$f(x,p;\alpha) = \frac{1}{N(T,\alpha)} \left\{ 1 + \alpha \left[\frac{mc^2(\gamma(p)-1) - e\varphi(x)}{T} \right] \right\} e^{-\frac{mc^2\gamma(p)+e\varphi(x)}{T}}$$

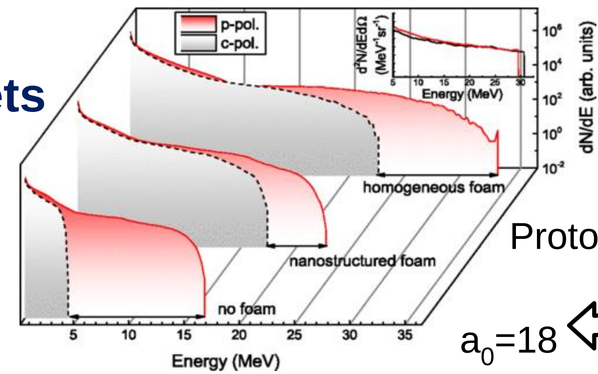
Deviation from equilibrium

→ Self-consistent quasi-static TNSA modeling
→ Hot electrons out of thermal equilibrium



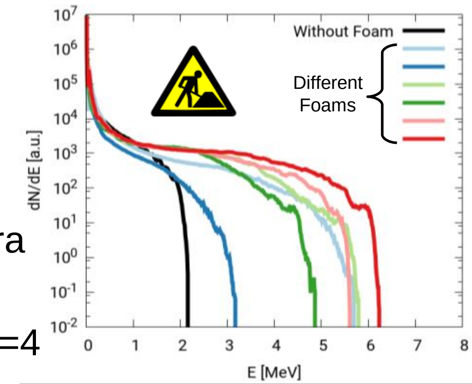
3D PIC simulations of ion acceleration with foam targets





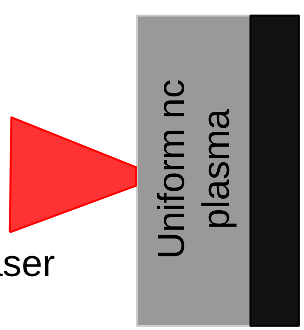
Proton spectra

a_0=18 a_0=4

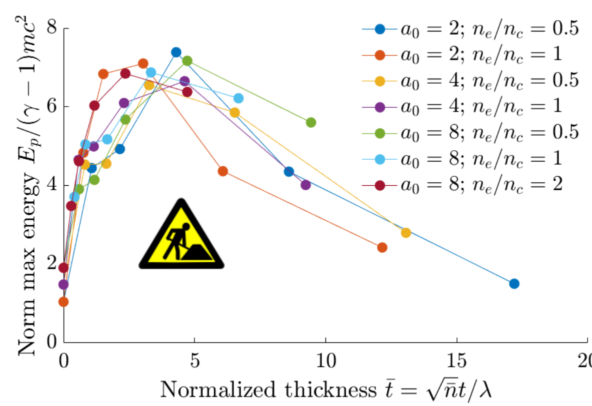


Extensive parametric 2D PIC campaign

L. Cialfi et al., *Phys. Rev. E* **94**, 053201 (2016)



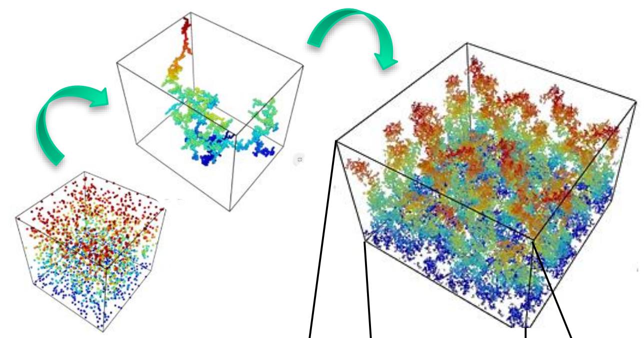
→ Self-similar scaling
→ Optimal density and thickness
→ Optimized parameters for a laser-ion accelerator



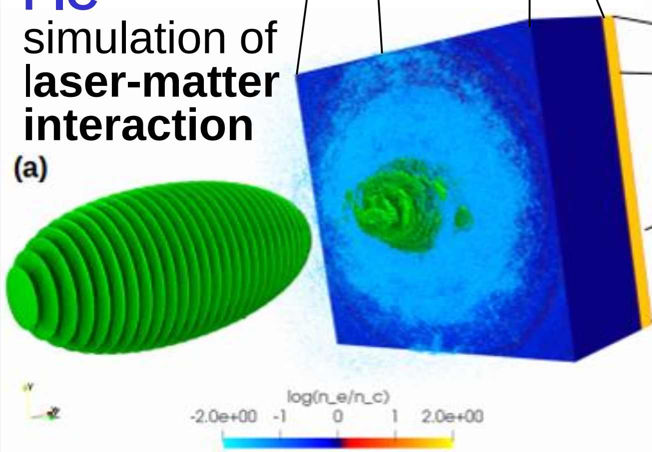
Application of laser-ion sources

A novel theoretical tool to study laser-ion sources for **nuclear** and **material science**

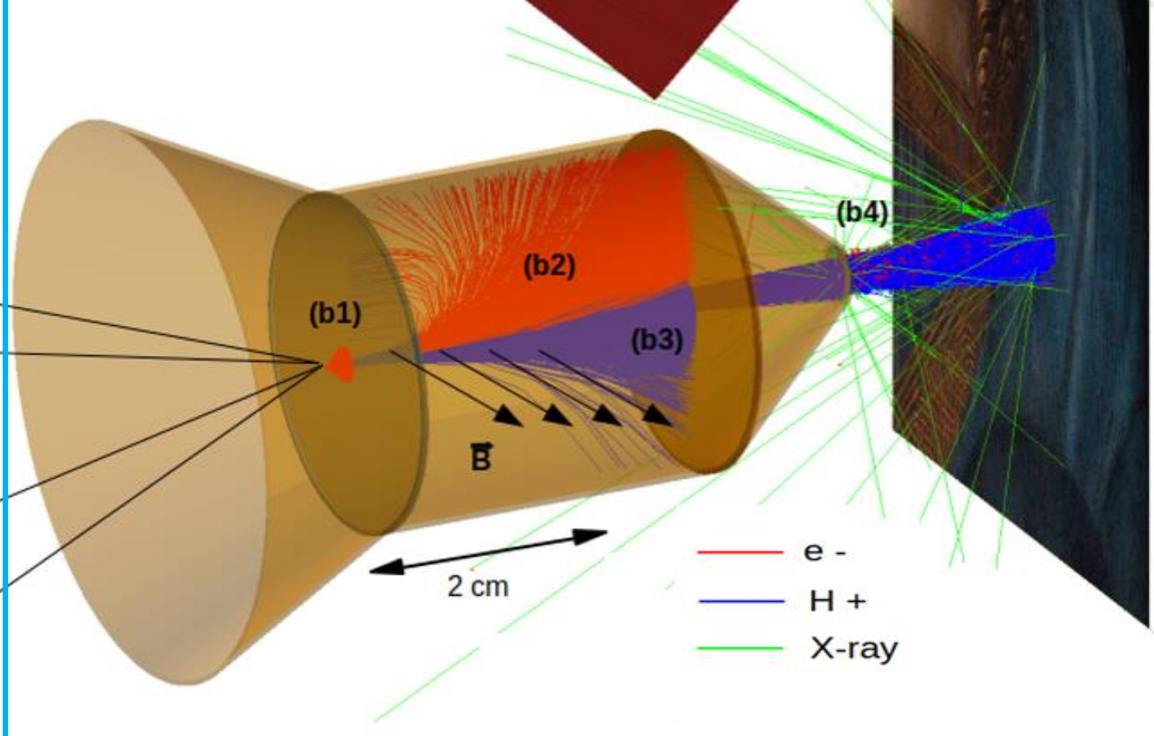
Simulation of **nanostructured materials aggregation/growth**



PIC simulation of **laser-matter interaction**

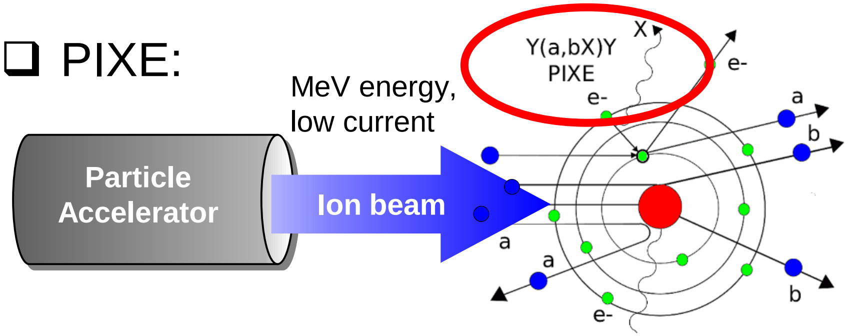


Monte Carlo simulation (Geant4) of **Laser-driven Ions interaction with matter.**



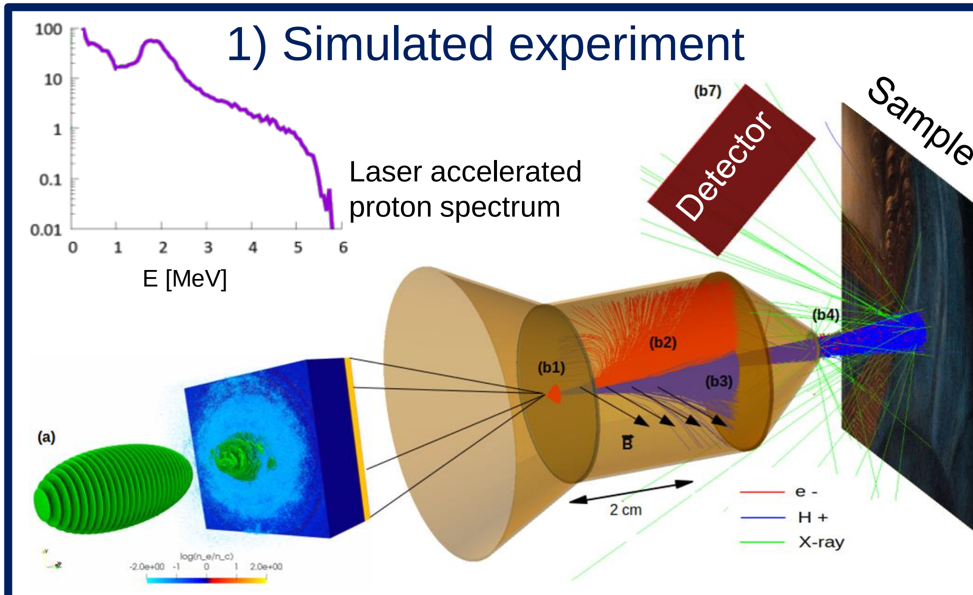
Laser-driven Particle Induced X-ray Emission (PIXE)

- PIXE:

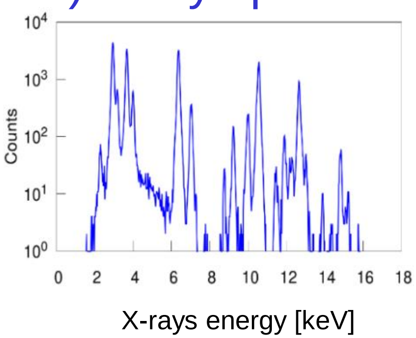


- Laser-driven PIXE:
  - ✓ **Unconventional features** of ion beam (broad spectrum, tunable energy, ns bunch duration)
  - ✓ **Cheaper, portable** PIXE setup
- Commercial codes not ok for laser PIXE
  - ✓ Ad-hoc code developed

1) Simulated experiment

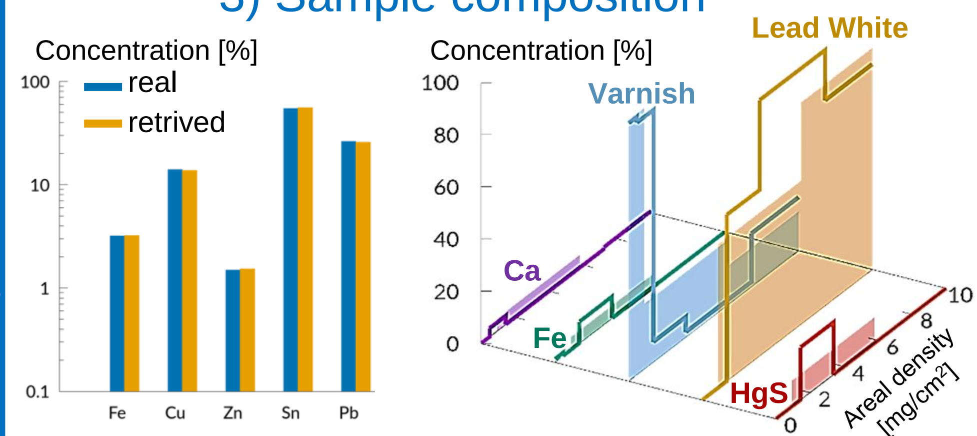


2) X-ray spectra



Dedicated **software** to process x-ray data

3) Sample composition



M. Passoni et al. *Scientific Reports*, **9**, 9202 (2019)

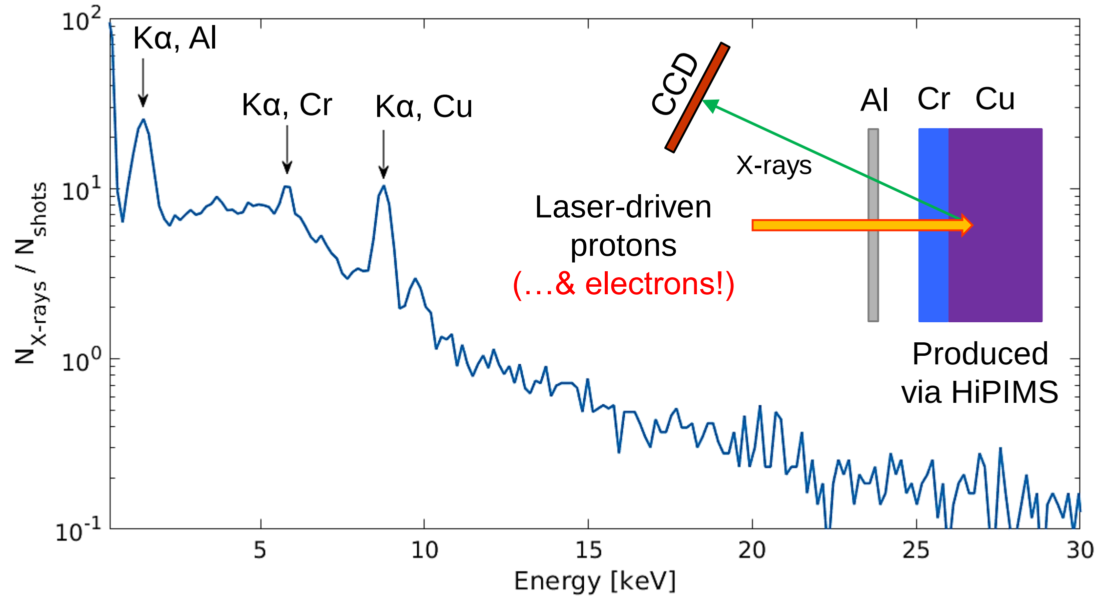
Laser-driven Particle Induced X-ray Emission (PIXE)

Recent experiment at

CLPU CENTRO DE LÁSERES PULSADOS

with VEGA-2 laser!

Preliminary data!

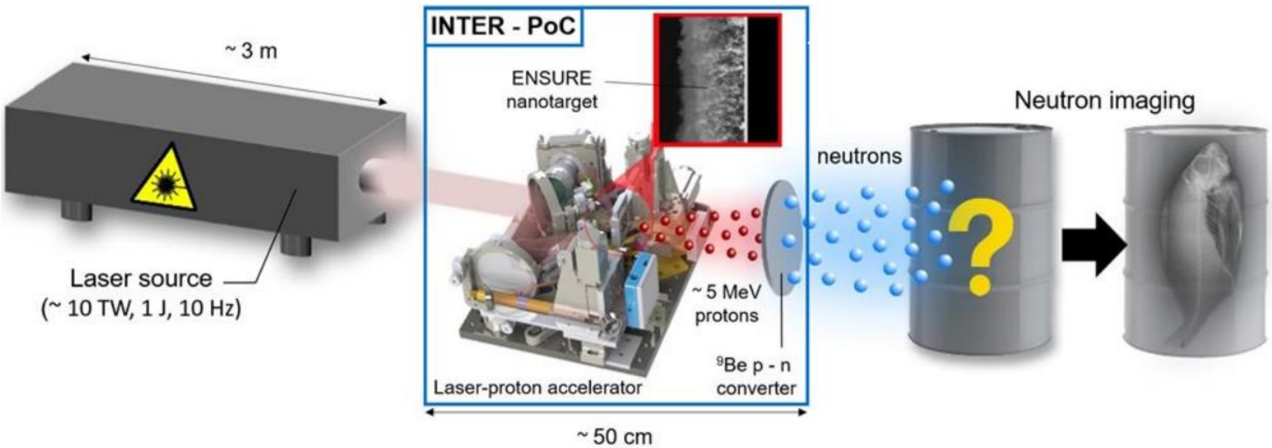


…other experiments foreseen also with industrial partners: SourceLAB

Need to address important aspects like:

- effective removal (and/or use) of the electrons;
- development of suitable detectors;
- in-vacuum vs in-air setup;
- …

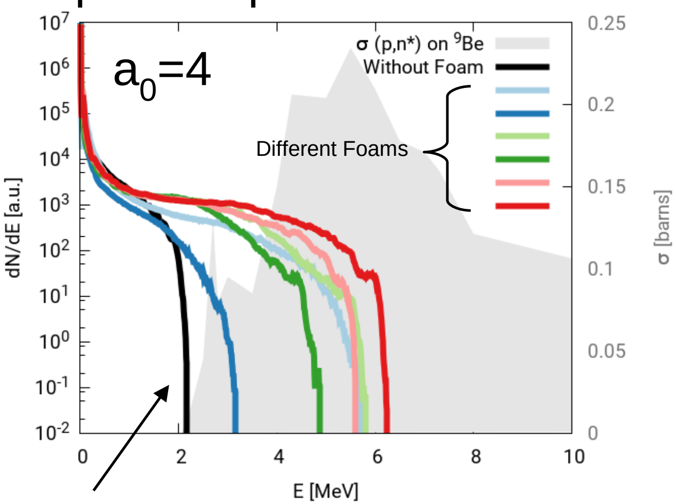
Towards portable neutron sources



ERC-2016-PoC No.754916

INTER

proton spectra from PIC



No foam: maximum energy below reaction threshold

- Foam targets may enable the neutron generation process
- Compact neutron sources for material characterization
  - fast-neutron spectroscopy
  - neutron radiography
- Studies with coupled PIC - Monte Carlo simulations
- Strong collaboration with industrial partners

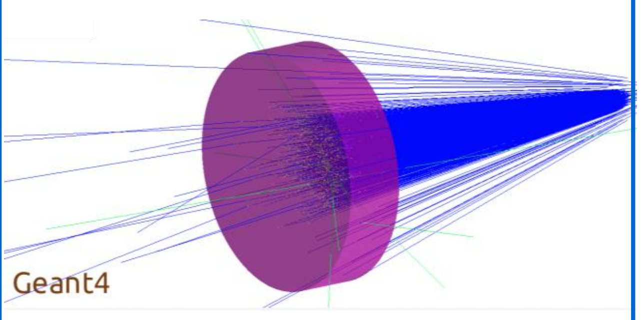
A. Tentori & F. M. Arioli, *MSc theses in Nuclear Engineering* (2018)

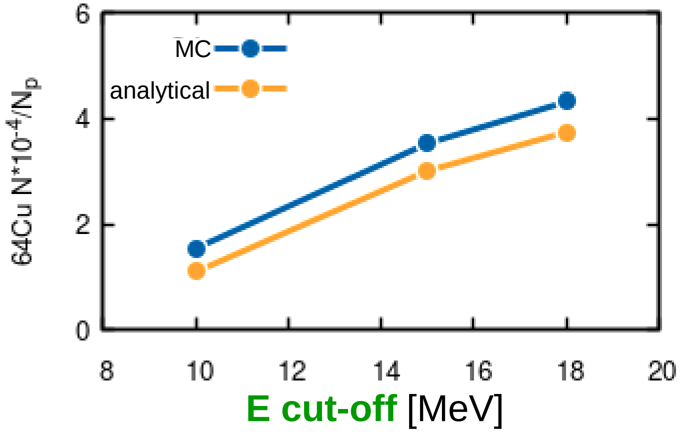
Laser-driven production of medical radioisotopes

→ Selected radioisotopes
- ^{64}Ni(**p**,n)^{64}Cu
- ^{11}B(**p**,n)^{11}C

Laser-driven **protons** are appealing!
- Cut-off energy $\mathbf{E_{c.o.}}$ 10s MeV
- Temperature **T** 1-10 MeV

Montecarlo simulations



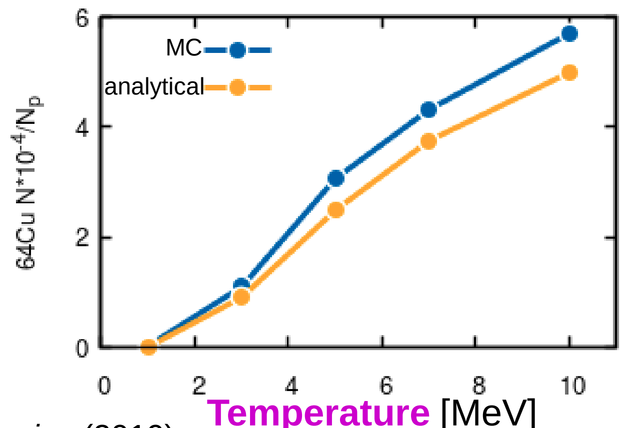


Reference spectra:
$\mathbf{E_{c.o.}}$ = 23.3 MeV
T=7.4 Mev
Rep Rate= 10 Hz

Analytical calculation

$$Y(E) = c_s\, N_t \int_0^E \frac{\sigma(\bar{E})}{S(\bar{E})} \mathrm{d}\bar{E}$$

$$N_i = \mathbf{n_p} \int_0^{\mathbf{E_{c.o.}}} Y(E) e^{-E/\mathbf{T}} \mathrm{d}E$$



→ **Preliminary results:**
25% of PET dose for ^{64}Cu
200% of PET dose for ^{11}C

A.C. Giovannelli, *MSc thesis in Nuclear Engineering* (2019)

Conclusions

- Control & optimization of **laser-plasma coupling is central** to develop laser-plasma based ion accelerators…target is the key!
- **nanostructured near-critical plasmas** are an appealing solution
- Need for **truly multi-disciplinary approach**: laser-plasma physics, material science, theory, simulation & experiments…
- Justified emphasis on the laser technology…but **plasma physics & target technology play and will play an essential role**
- Some **applications of compact laser-ion accelerators** can be realistically not so far!

The ENSURE team at Politecnico di Milano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erc ERC-2014-CoG No. 647554
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Former team members


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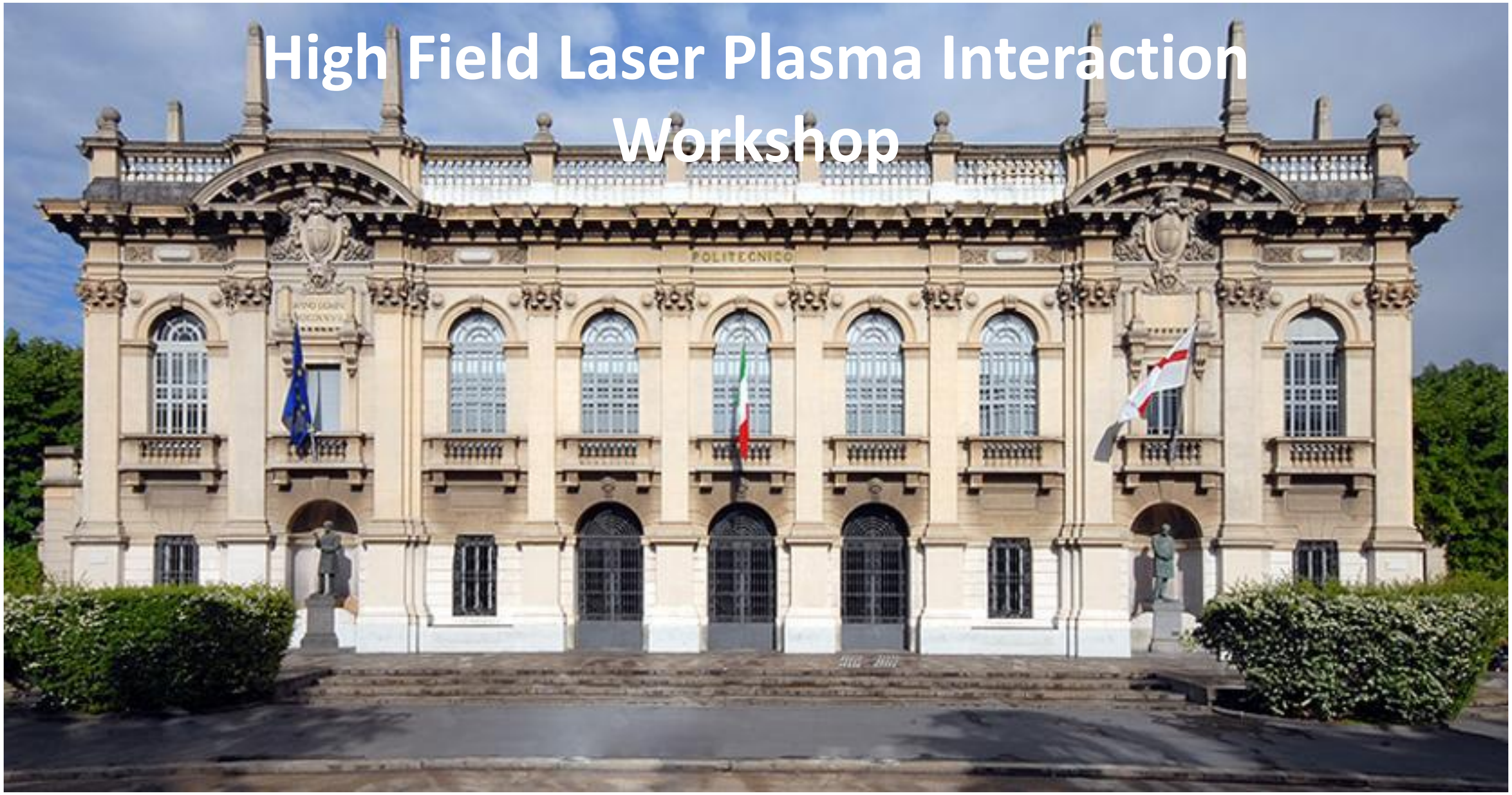
L. Cialfi

High Field Laser Plasma Interaction Workshop



Saturday 13, **July 2019**

Politecnico di Milano, **Milano, Italy**

Chairs: Marija Vranic, Mickael Grech, Matteo Passoni

EPS

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MILANO 1863
DIPARTIMENTO DI ENERGIA

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High Field Laser Plasma Interaction Workshop

Thank You!

Saturday 13, **July 2019**

Politecnico di Milano, **Milano, Italy**

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Foam property control with PLD

Nano-scale

- Crystalline structure
- Composition

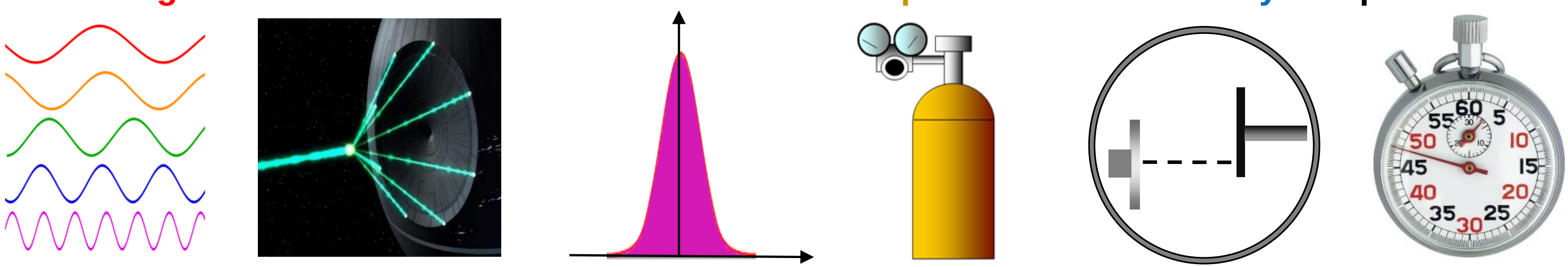
Micro-scale

- Average density
- Morphology
- ....

Macro-scale

- Uniformity
- Thickness profile

Wavelength **Laser Fluence** **Pulse duration** **Gas pressure** **Geometry** **Deposition time**



PLD process parameters