POLITECNICO
MILANO 1863

Advances in superintense laser interaction with nanostructured foams

Matteo Passoni
Trento, 15/09/2017

Aims and outline of the talk

- Introduction to superintense laser-matter interaction

- Superintense laser-driven ion acceleration

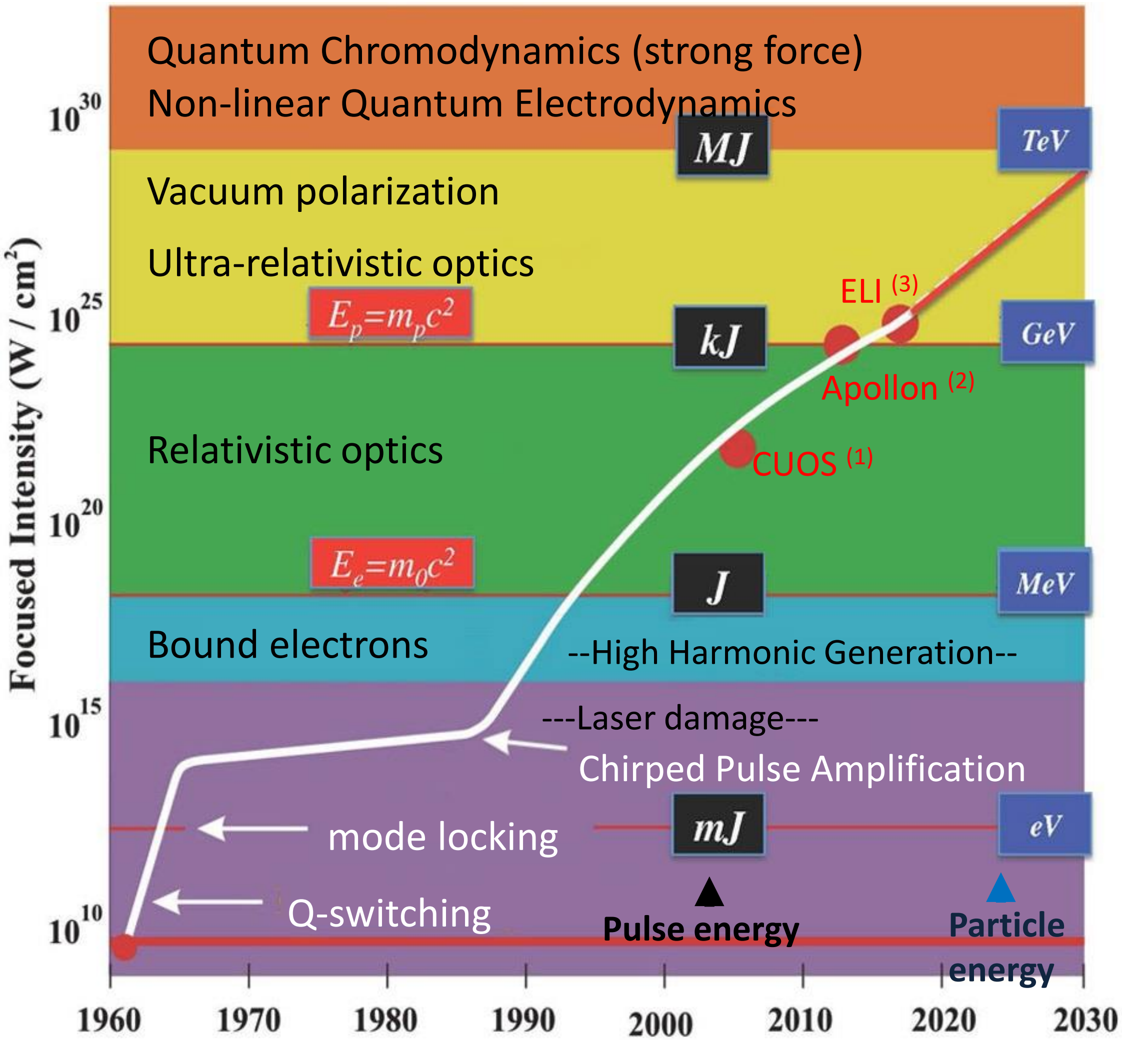
- The ENSURE and INTER projects @ POLIMI

- Laser-ion acceleration with multi-layer, nanostructured foam-based targets

- Concluding remarks

Superintense laser-matter interaction

New physics available by progress in laser technology



(1) CUOS: Center for Ultrafast Optical Science (University Michigan)
(2) Apollon Laser, Centre Interdisciplinaire Lumière Extrême (France)
(3) Extreme Light Infastructure (EU) https://eli-laser.eu/

Important laser quantities

Typical laser parameters with Chirped Pulse Amplification (since '80s)

Laser wavelength (μm): ≈ 1 (Nd-Yag), 0.8 (Ti-Sa), ≈ 10 (CO_2)

Energy (per pulse): 10^{-1} - 10^{3} J

Pulse duration: ≈ 10 - 10^{3} fs (at $\lambda = 1$ μm, $\tau = c/\lambda = 3.3$ fs)

Power: ≈ 100 TW - few PW (PW lines now available)

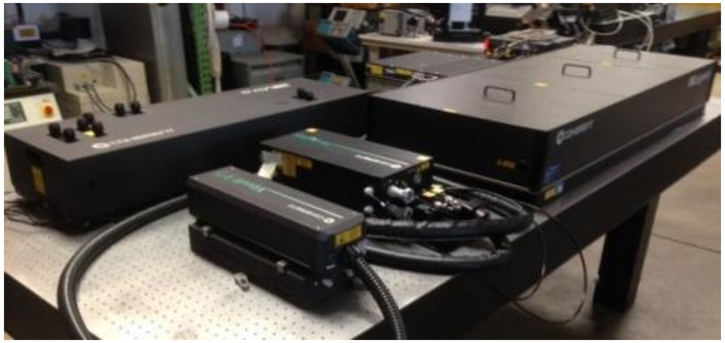
Spot size at focus: down to diffraction limit → typically ø < 10 μm

Intensity (power per unit area): 10^{18} W/cm^2 up to 10^{22} W/cm^2

From huge facilities……

Nova laser, LLNL, 1984

… to table-top systems!



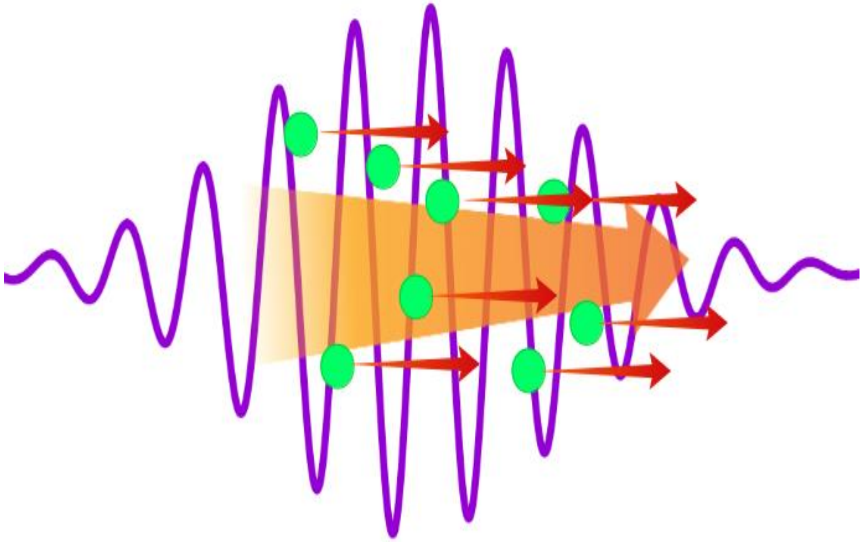
Commercial TW class laser, 2010s

The strength of laser fields:

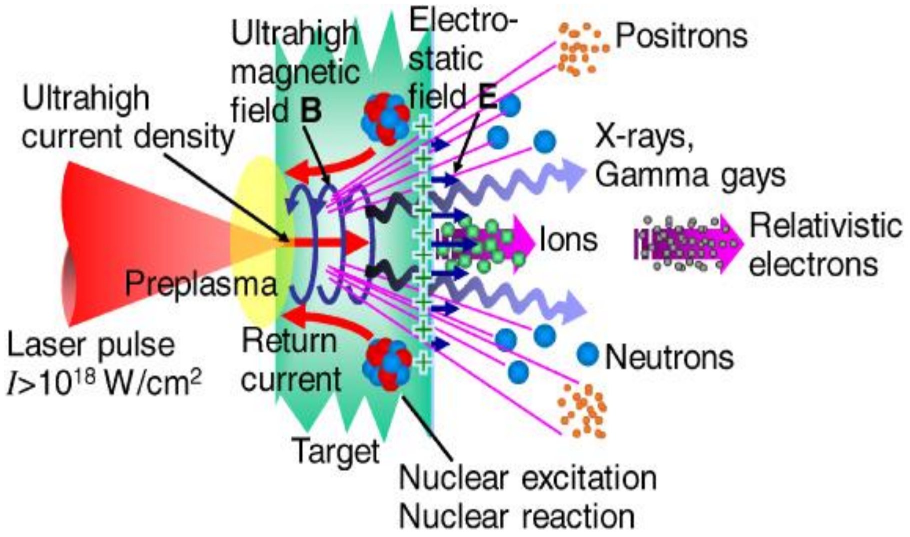
Laser field vs. "relativistic" field

Relativistic field →

$$\frac{m_e \omega c}{e} \cong \frac{3.2\times 10^{10}}{\lambda(\mu\mathrm{m})}\,\frac{\mathrm{V}}{\mathrm{cm}} \Rightarrow I \cong \frac{1.4\times 10^{18}}{\lambda^2(\mu\mathrm{m})}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$$



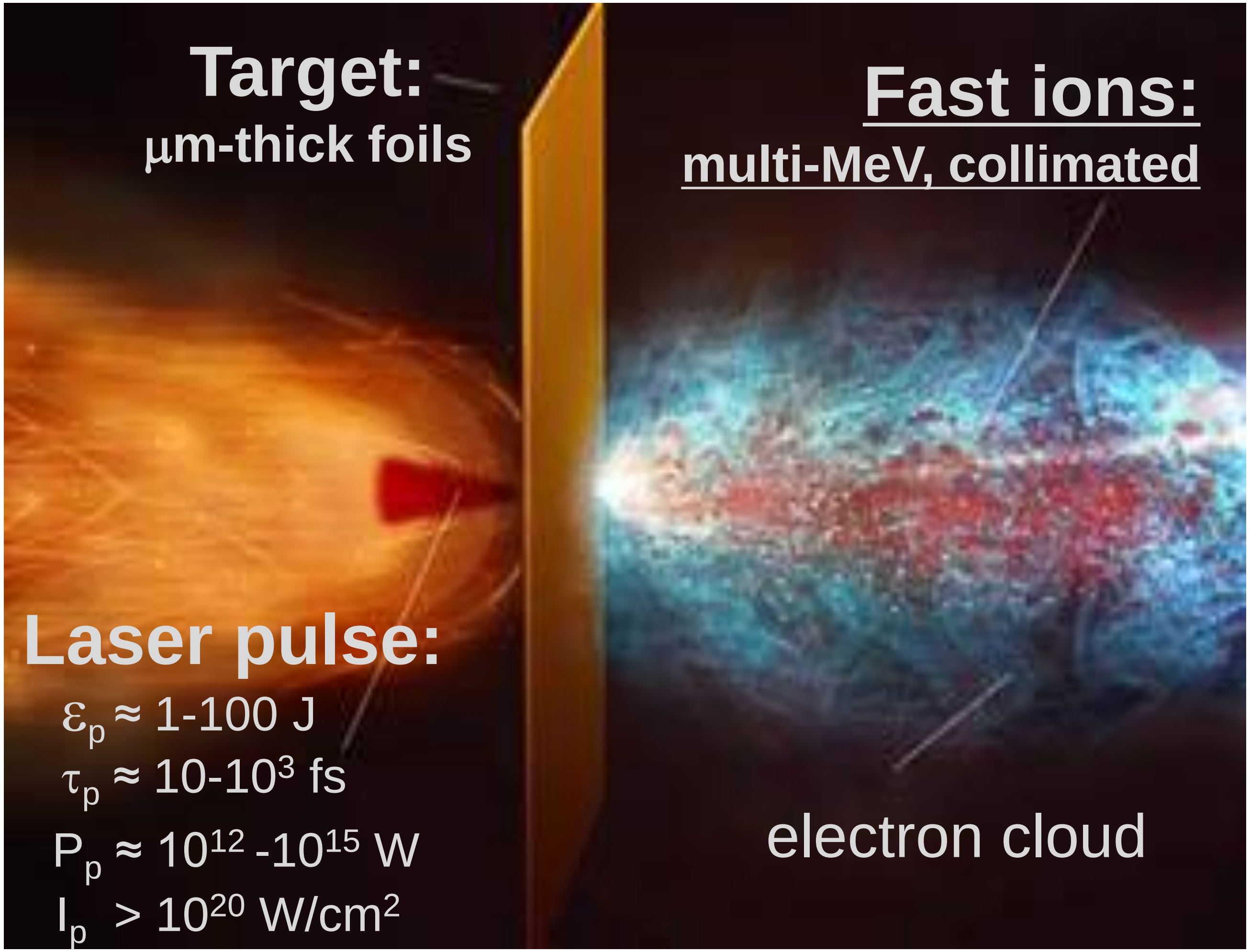
Relativistic electron momenta (p ~ mc) in one laser cycle



Hiroyuki Daido and Mamiko Nishiuchi and Alexander S Pirozhkov. Review of laser-driven ion sources and their applications , Reports on Progress in Physics 75(5), 056401 (2012)

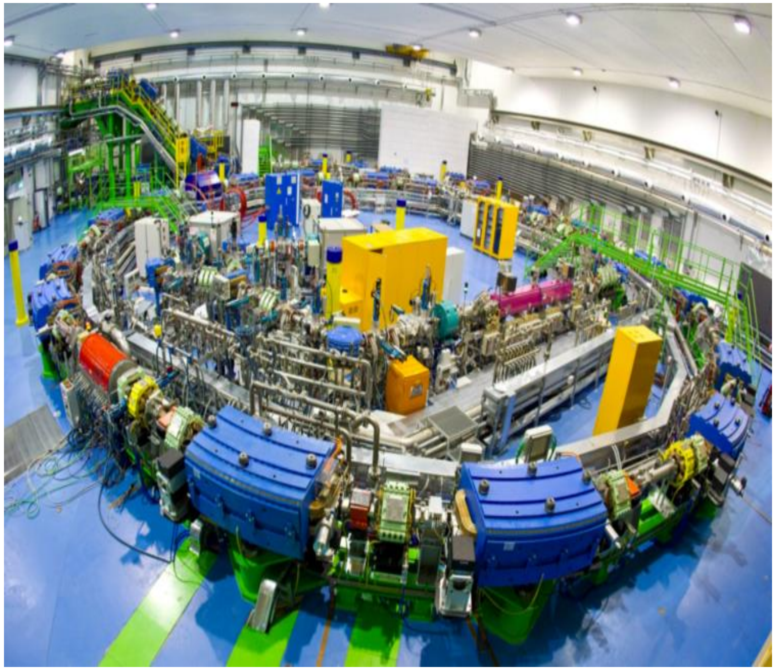
Laser-driven ion acceleration

A non conventional way to accelerate heavy charged particle beams



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

Conventional ion accelerators:



CNAO Synchrotron (Pavia)

High-energy particle beams crucial for:

- Medicine: radiotherapy, nuclear diagnostics,…
- Material engineering: ion beam analysis, implantation
- Nuclear engineering: Inertial Confinement Fusion,…
- Basic science: particle & high energy physics,…

Laser-driven ion accelerator:

Appealing potential:

- Compactness
- Cost effectiveness
- Flexibility

Critical issues:

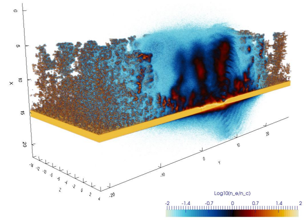
- Gain control of the process
- Increase efficiency/performance
- Limitation and cost of lasers

Novel targets can be the key!

I. Prencipe et al, High Power Laser Science and Engineering, **5** 1 (2017)

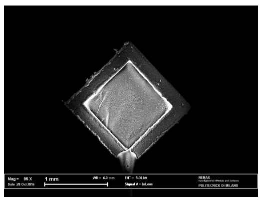
ERC-2014-CoG No. 647554

The ENSURE project @ Politecnico di Milano



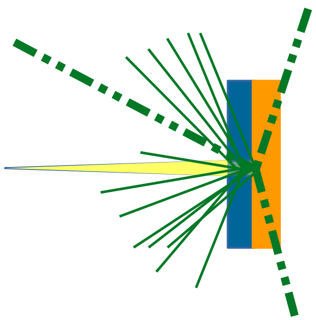
Laser-driven ion acceleration

Theoretical/numerical & experimental investigation



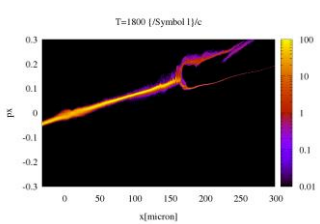
Materials science

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[...]

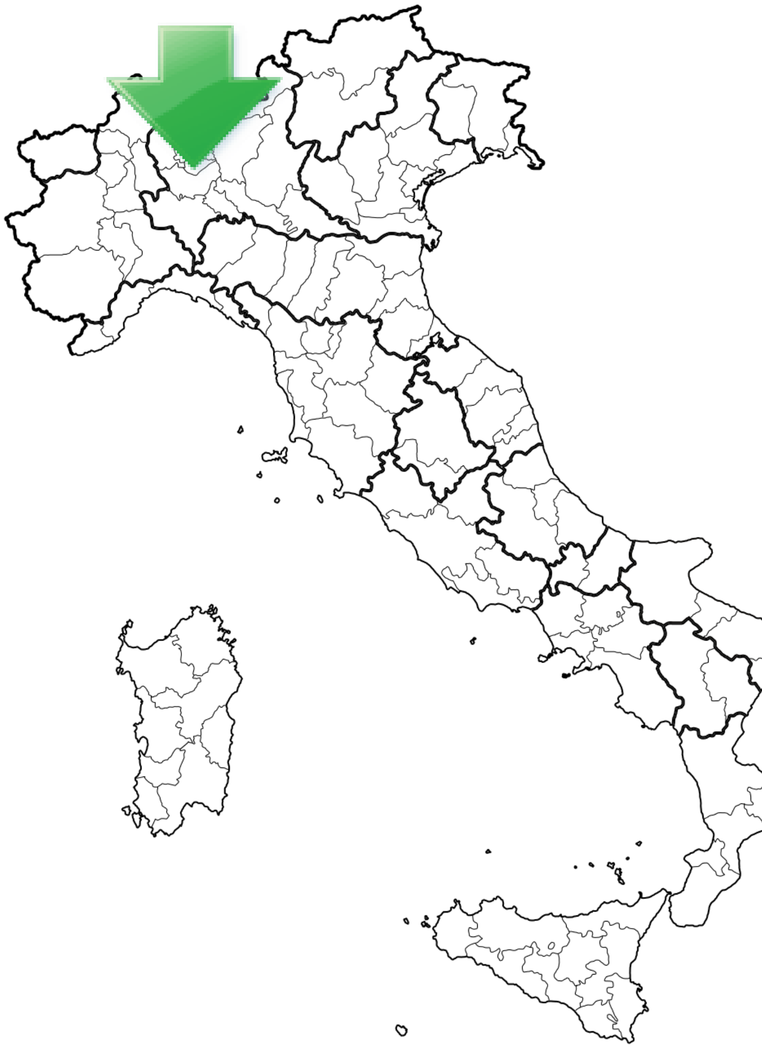


Fundamental physics and laboratory astrophysics

Laser interaction with (near-critical) nanostructured plasmas
Collisionless shock acceleration of ions

The ENSURE team @ Politecnico di Milano

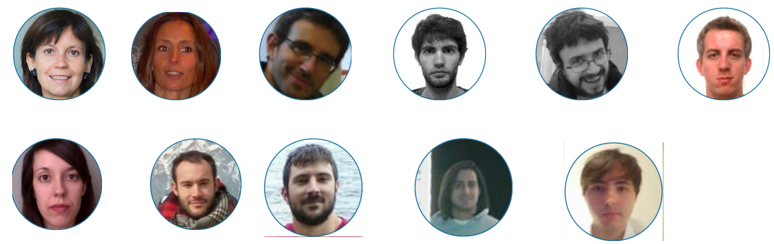
Milano



Matteo Passoni

Associate professor

ERC-2014-CoG No.647554
ENSURE
ERC-PoC: **INTER**



Ongoing collaborations with:

HZDR

OSAKA UNIVERSITY

SourceLAB

Queen's University Belfast

The ENSURE team @ Politecnico di Milano

Matteo Passoni
Associate professor

erc ERC-2014-CoG No.647554
ENSURE

Margherita Zavelani-Rossi
Associate professor

Valeria Russo
Researcher

4 Post-docs

D. Dellasega

A. Maffini

L. Fedeli

L. Cialfi

3 PhD students

A. Formenti

A. Pazzaglia

F. Mirani

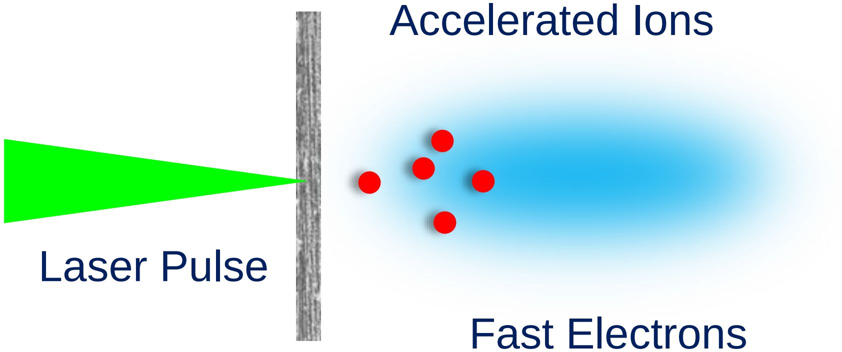
2 Master's students

A. Tentori

M. Sala

Enhanced Target Normal Sheath Acceleration

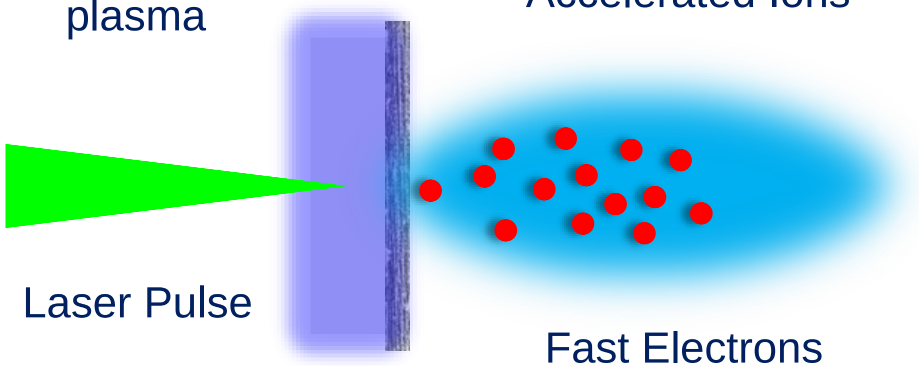
Conventional Target



Solid Foil
Surface interaction mechanisms

Target Normal Sheath Acceleration (TNSA)

Multi-layer near critical Target



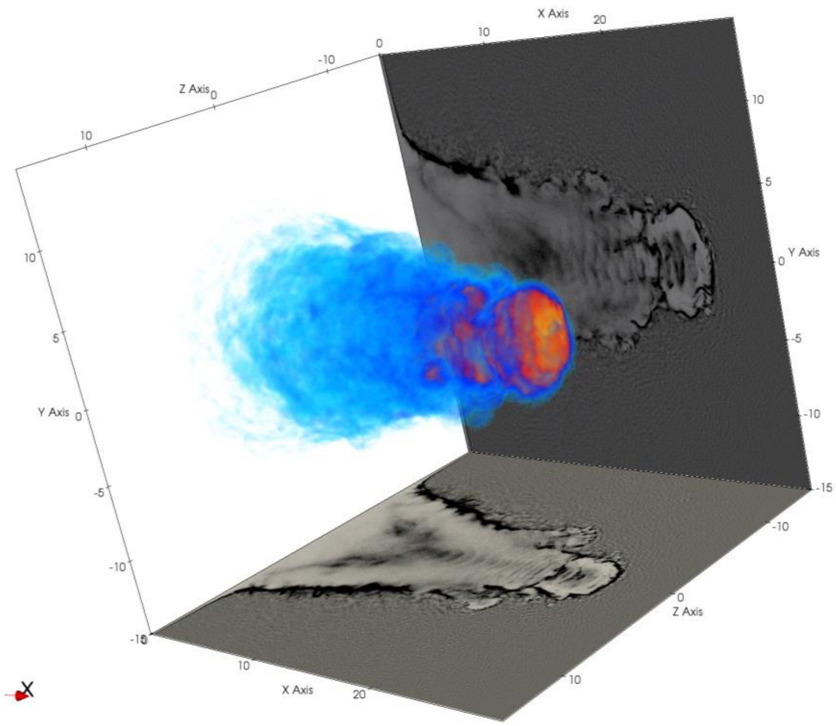
Solid Foil + Low Density Layer
Volume & Surface Interaction Mechanisms

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)

Laser interaction with near-critical plasmas is interesting for several applications...



Why bother with near-critical plasmas?

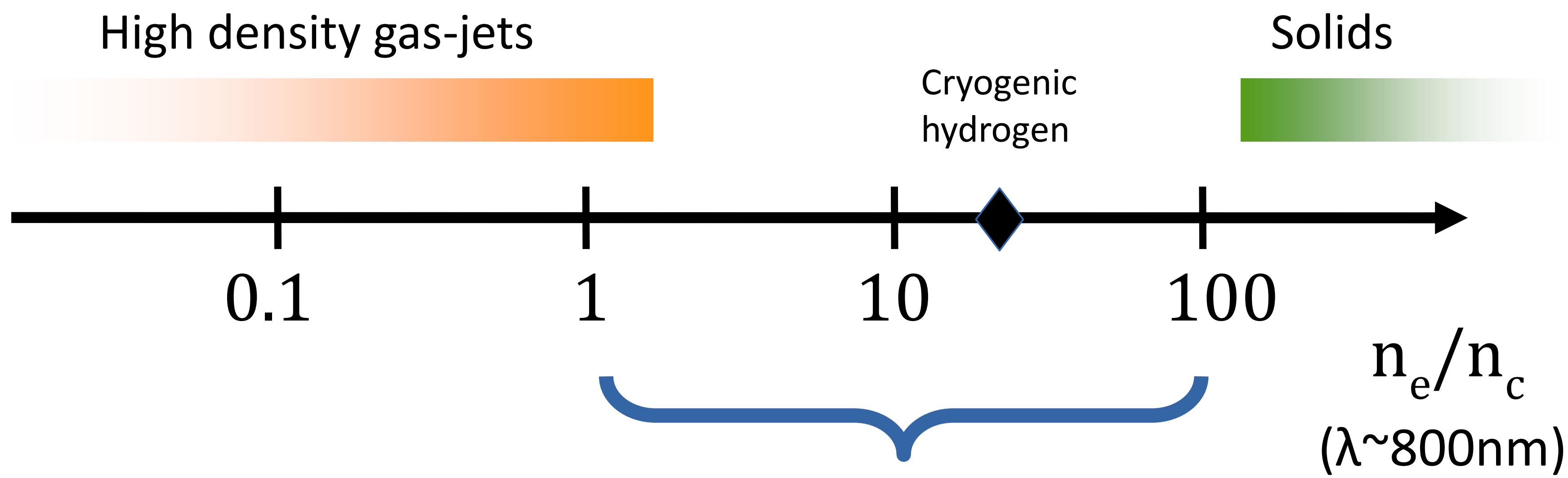
Several interesting applications:

- Enhanced ion acceleration
- Laboratory astrophysics
- γ-ray sources
- Inertial confinement fusion
- Electron acceleration

...

ERC-2014-CoG No. 647554

...from near critical plasma to low density materials

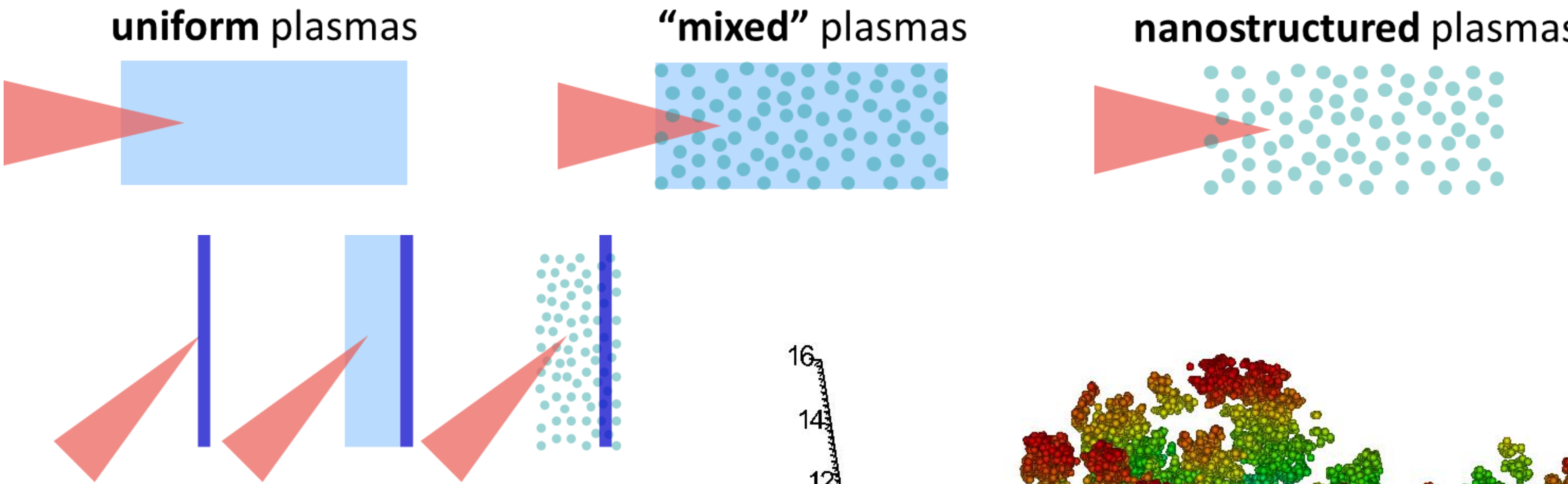


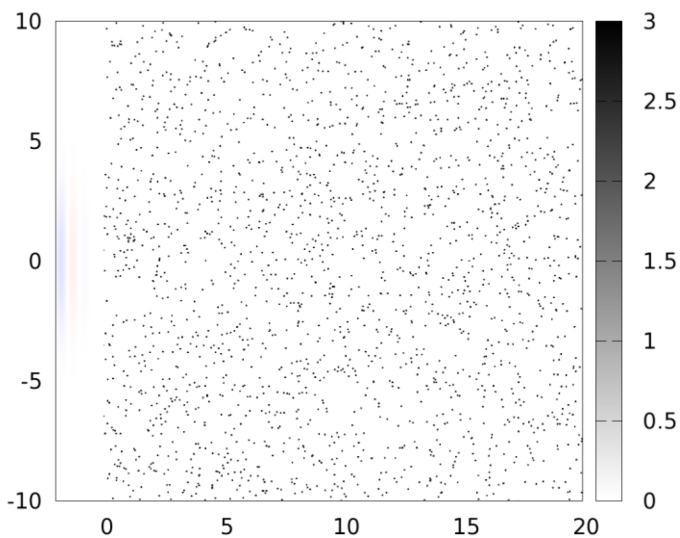
Few options:

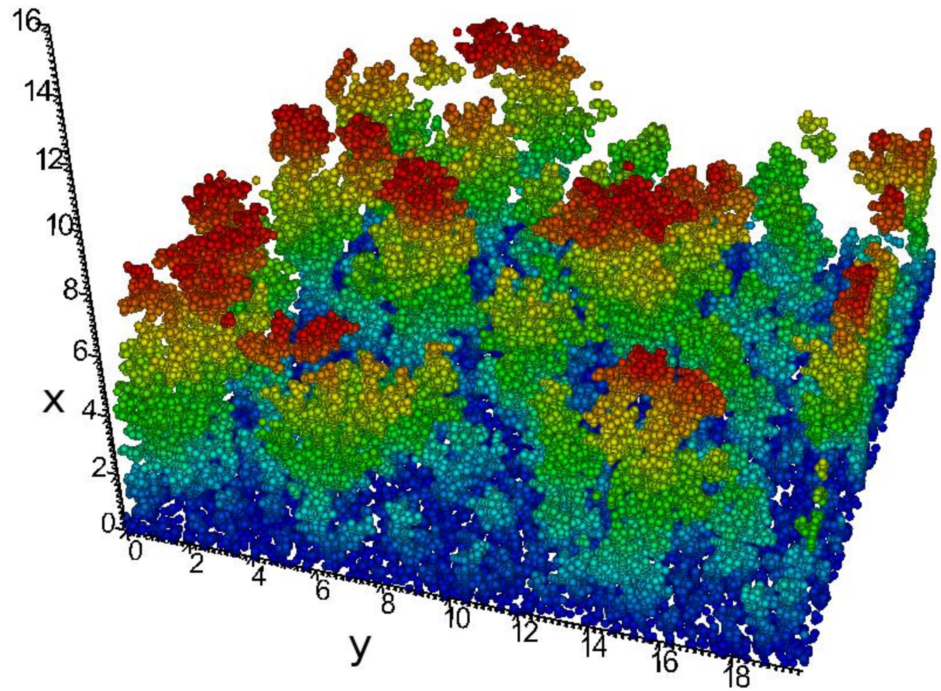
- Pre-heating
- **Very low-density nanostructured materials with 1/500th density of solids**
  - Aerogels[1]
  - Nanotube arrays[2]
  - Foams[3]

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

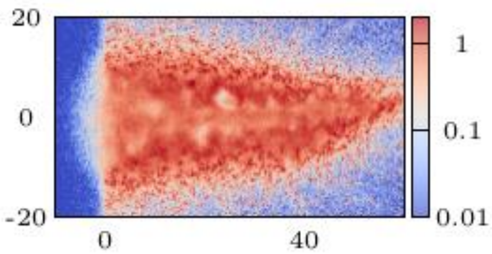
Idealized modeling vs “realistic” modeling



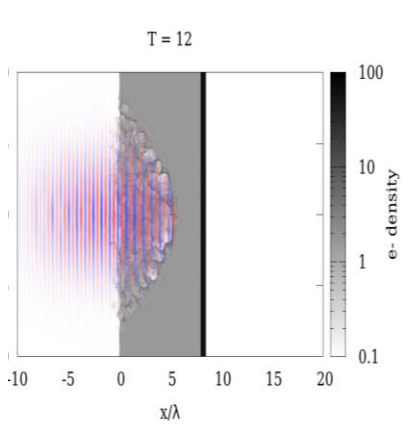




Idealized modeling



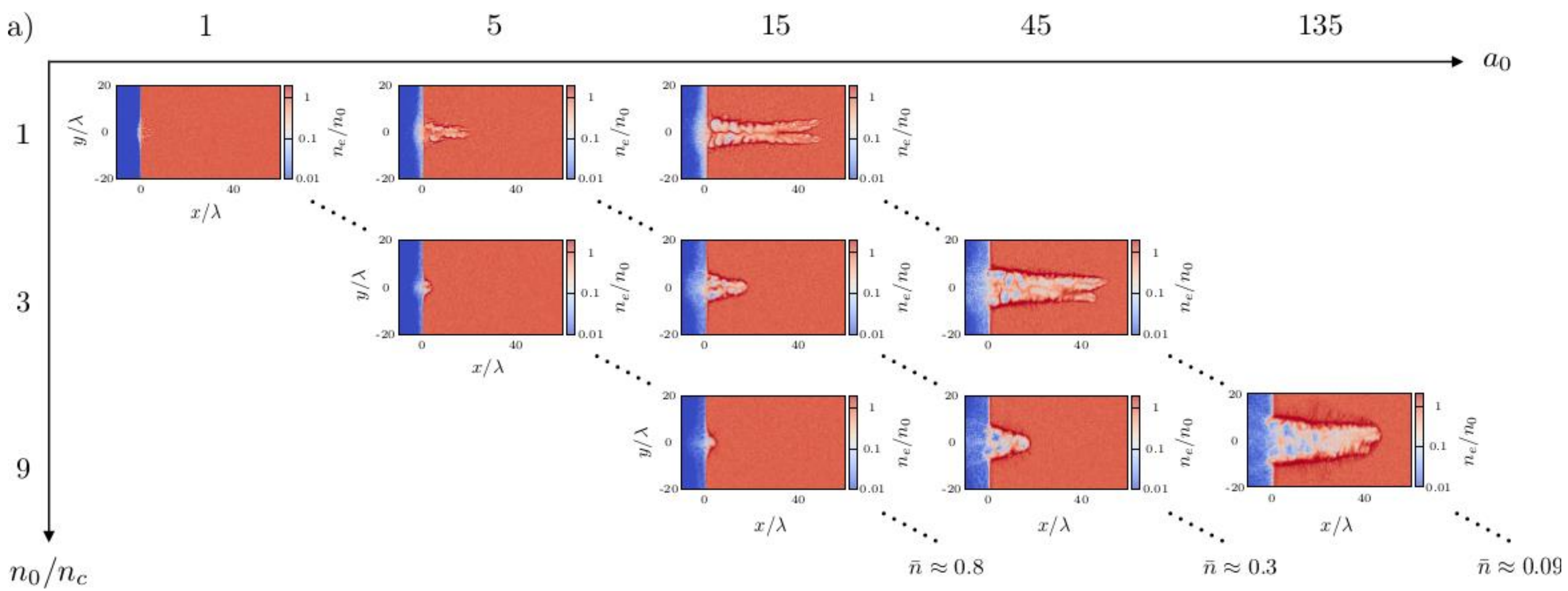
Laser propagation in uniform and nanostructured near-critical plasmas
L.Fedeli, A.Formenti, C.E.Bottani & M.Passoni
Topical Issue on "Relativistic Laser Plasma Interactions", Europ. Phys. Journal D (2017)



Electron heating in foam-attached targets
L.Cialfi, L.Fedeli & M.Passoni Phys.Rev.E 94 (2016)

https://github.com/ALaDyn/piccante

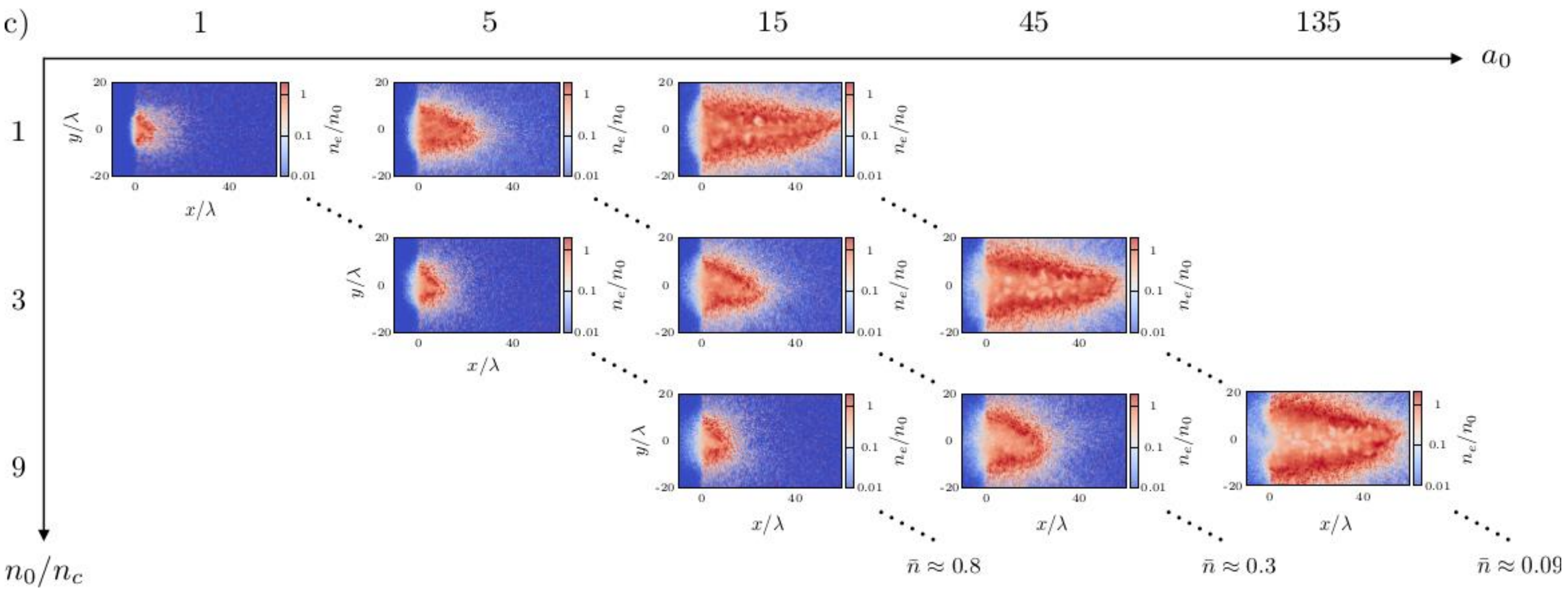
Wide range of laser intensities and average densities



Uniform plasma

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

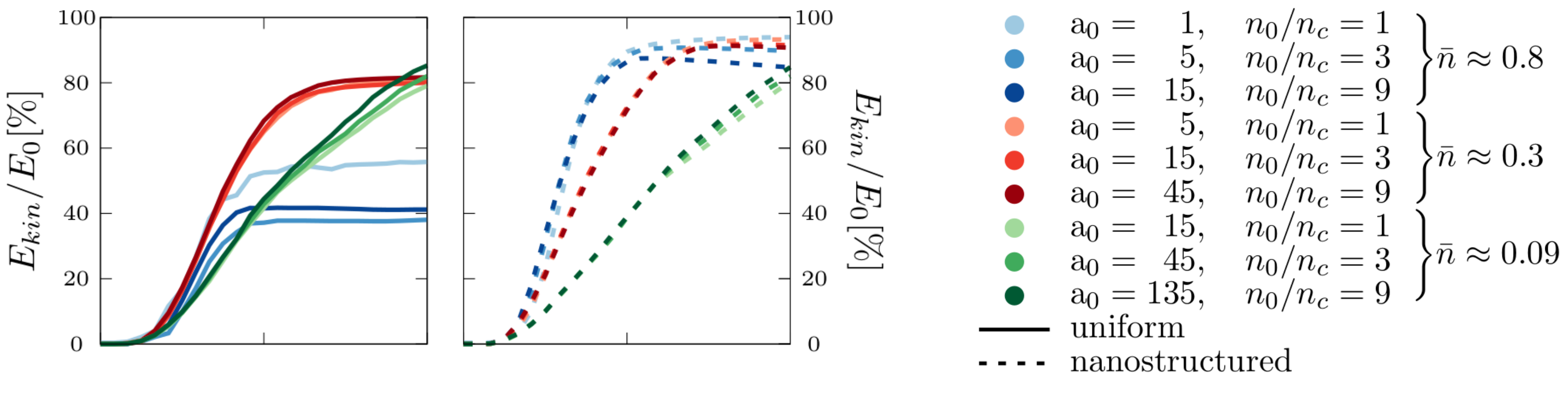
Wide range of laser intensities and average densities

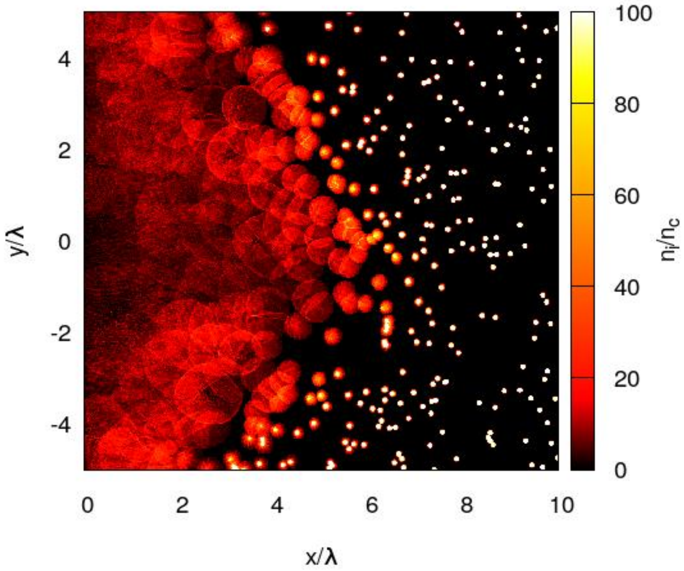


Nanostructured plasma

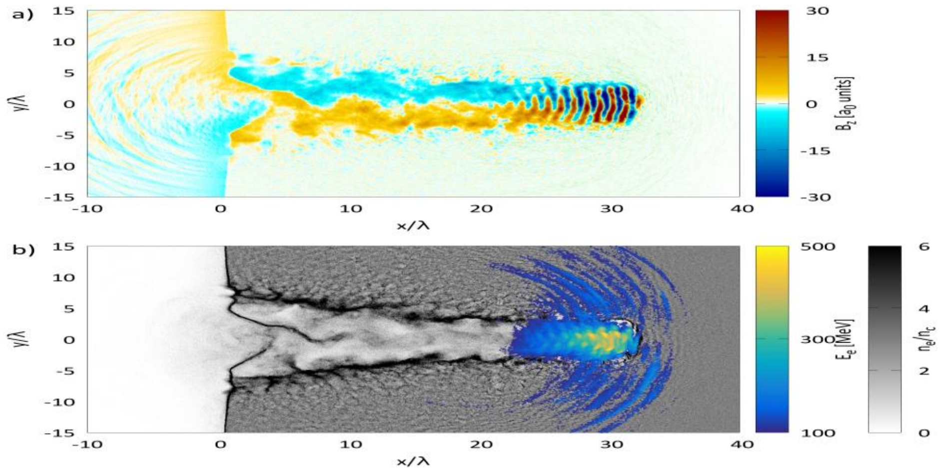
$$\bar{n} = \frac{n_e / n_c}{\sqrt{1 + a_0^2 / 2}}$$

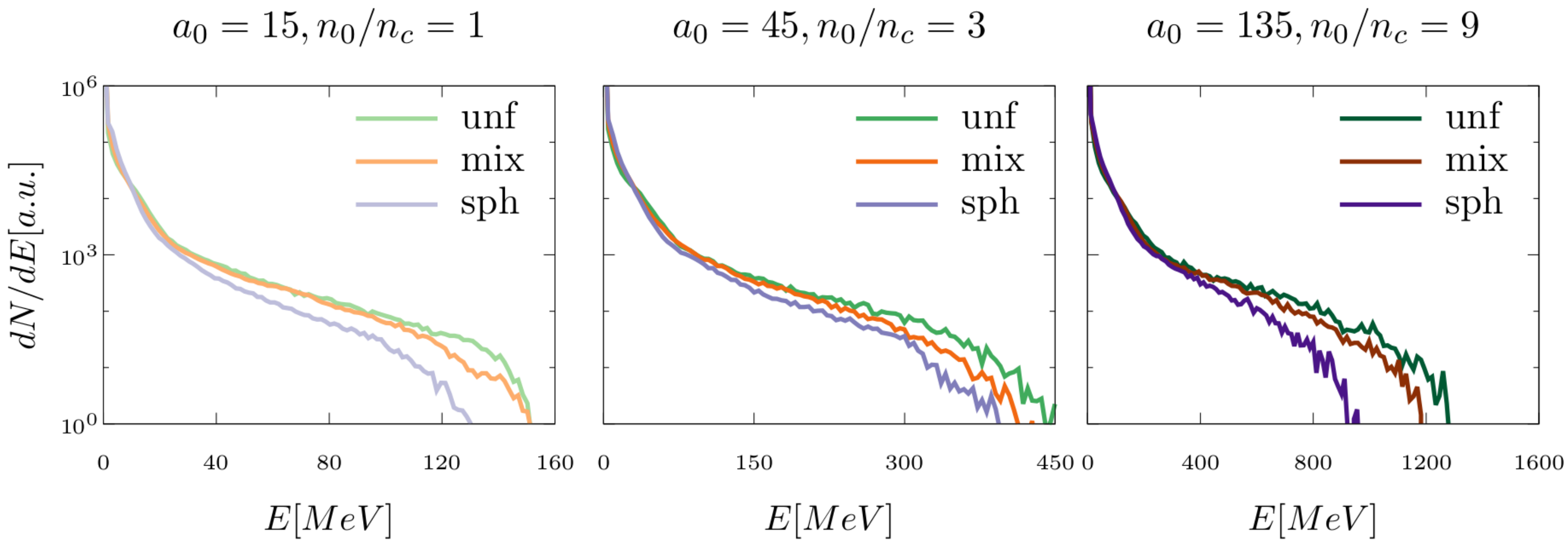
Main differences appear for partitioning of absorbed energy...





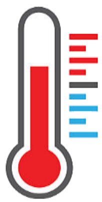
...and for the tail of electron energy spectra





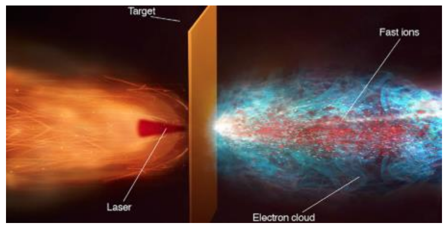
A very similar approach was followed to simulated electron heating in near-critical foam-attached targets

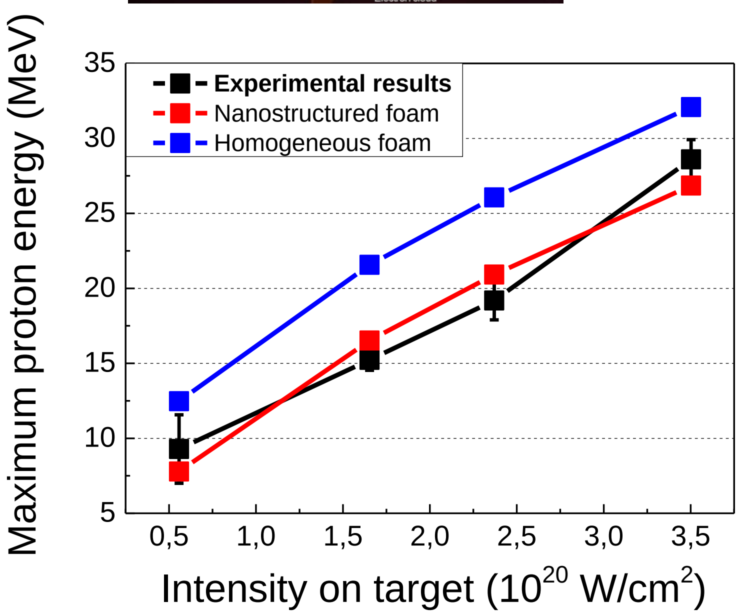
e^- temperature from PIC sim.



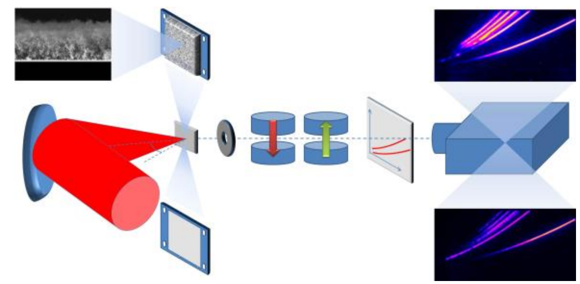
+

TNSA ion acceleration model*





Benchmark with exp.

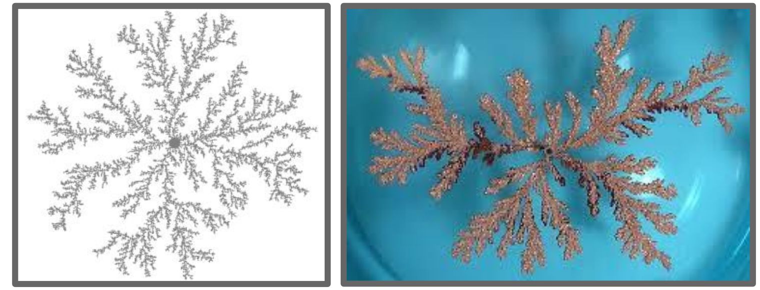


I.Prencipe et al. PPCF 58 (2016)
M.Passoni et al. PRAB 19 (2016)

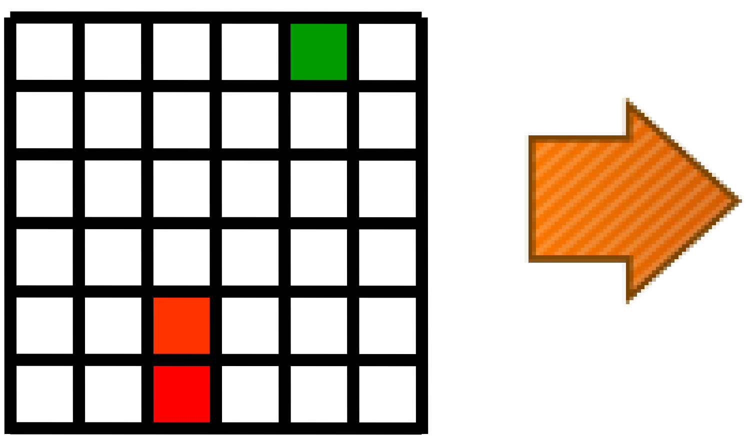
*quasi-static
Passoni-Lontano model
Phys. Rev. Lett. 101 (2008)

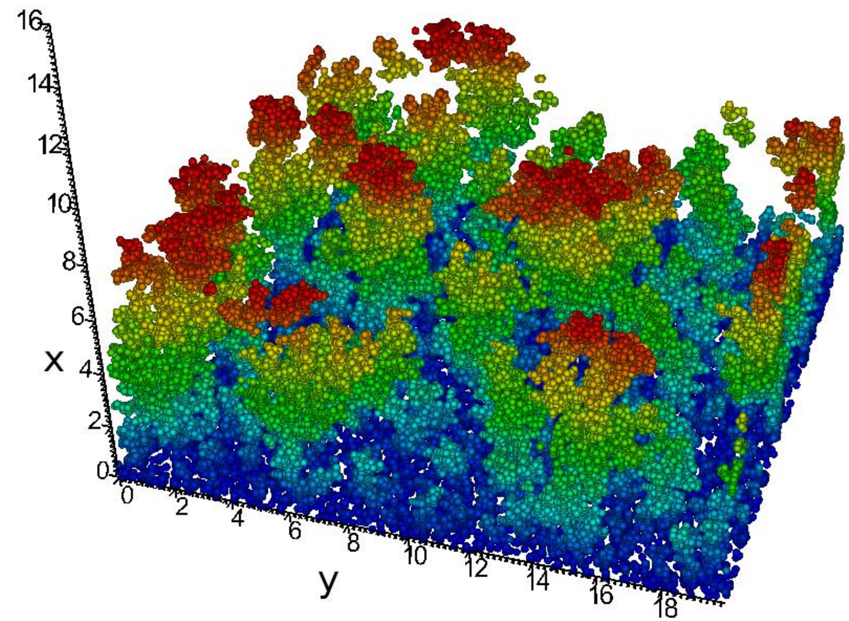
“Realistic” modeling based on DLA

Diffusion Limited Aggregation (DLA)
A simple and very well studied model to reproduce structures resulting from aggregation phenomena.



Witten&Sander,PRL 47 , 1981

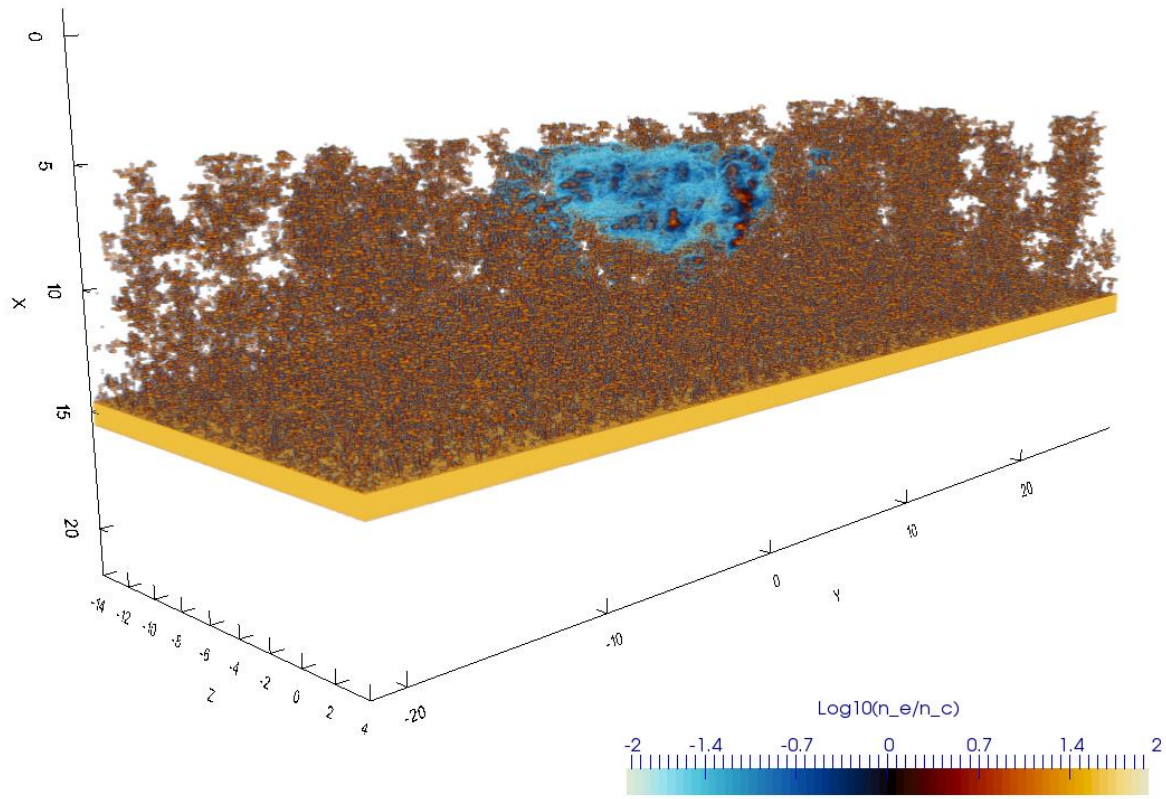




Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

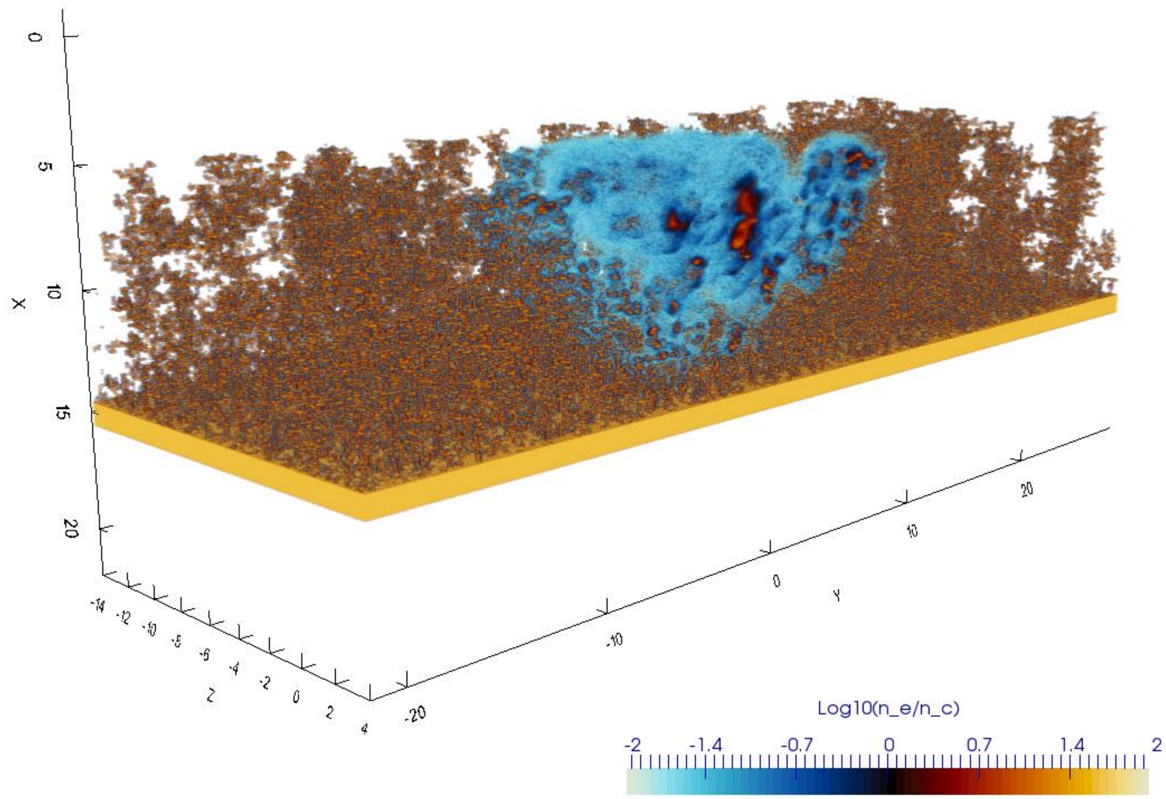
T = 08 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

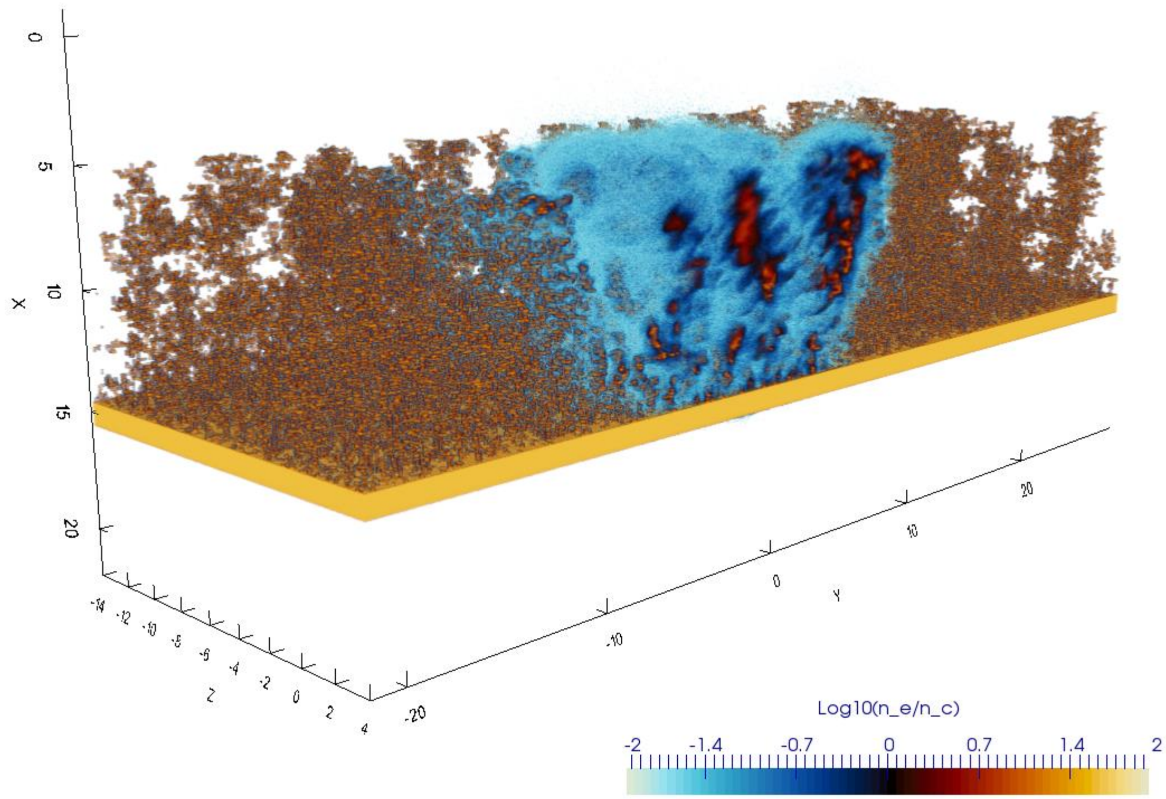
T = 12 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

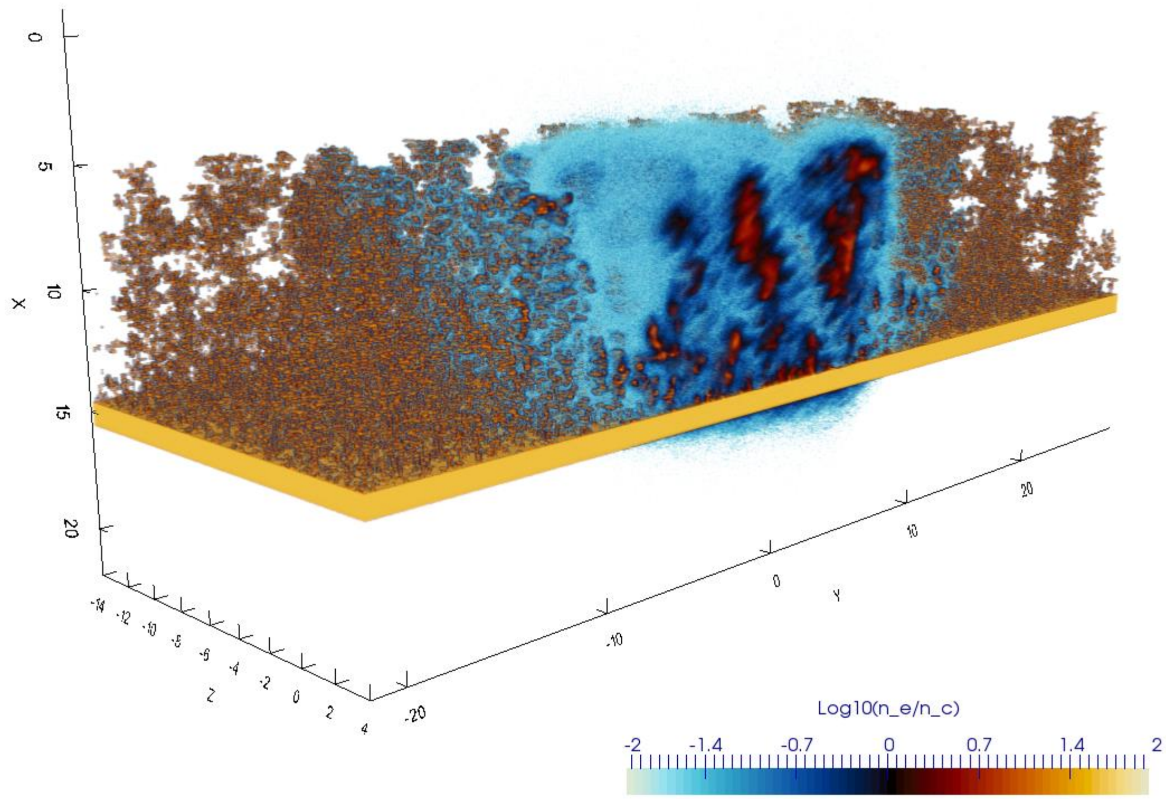
T = 16 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

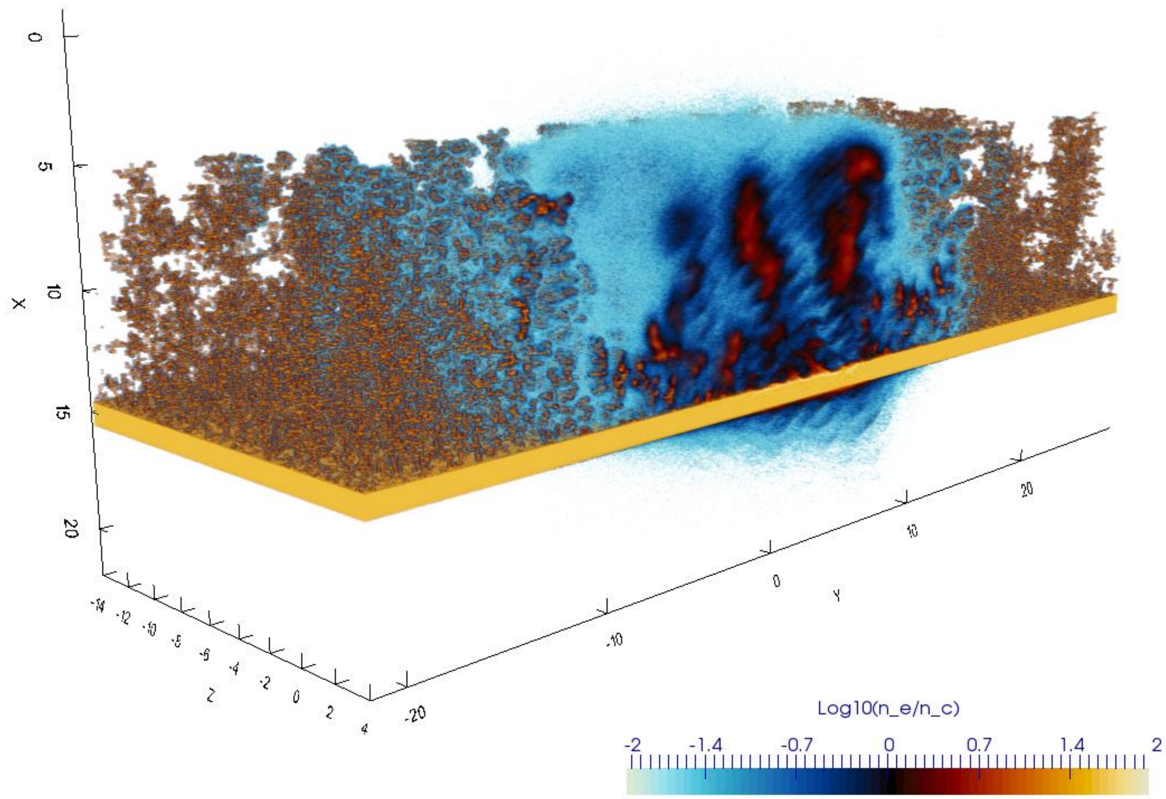
T = 20 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

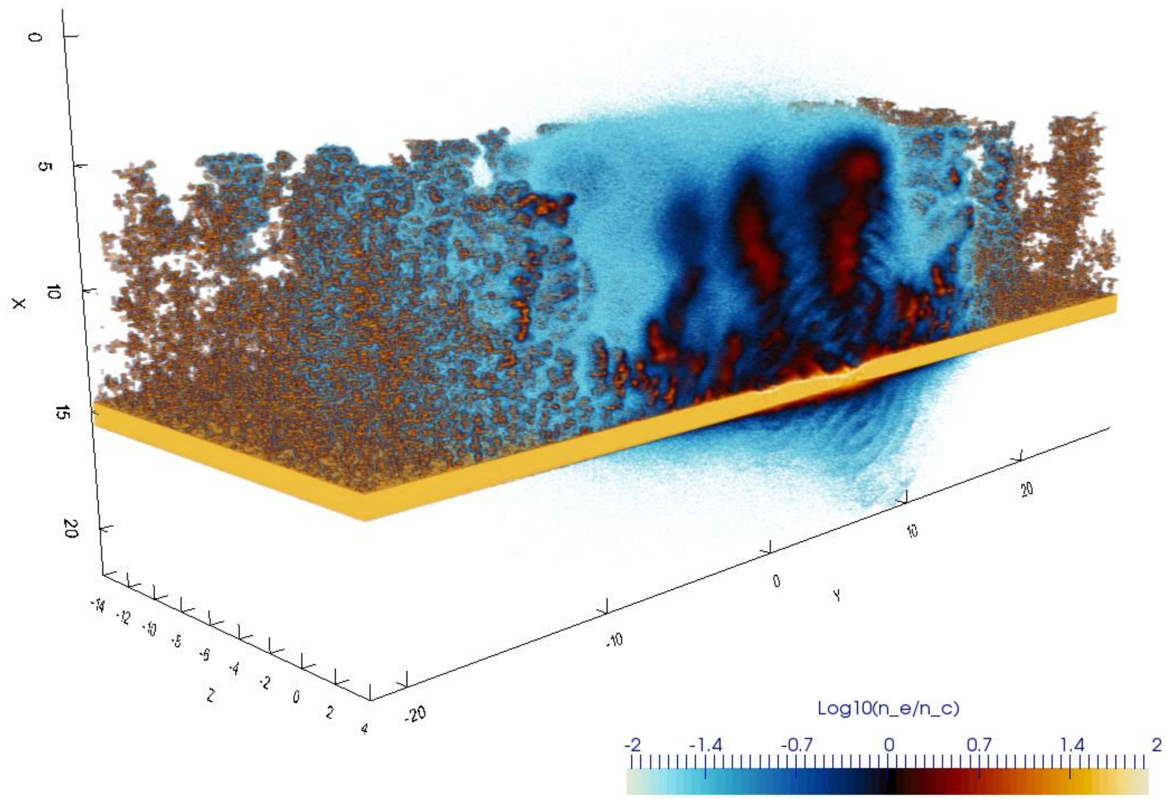
T = 24 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

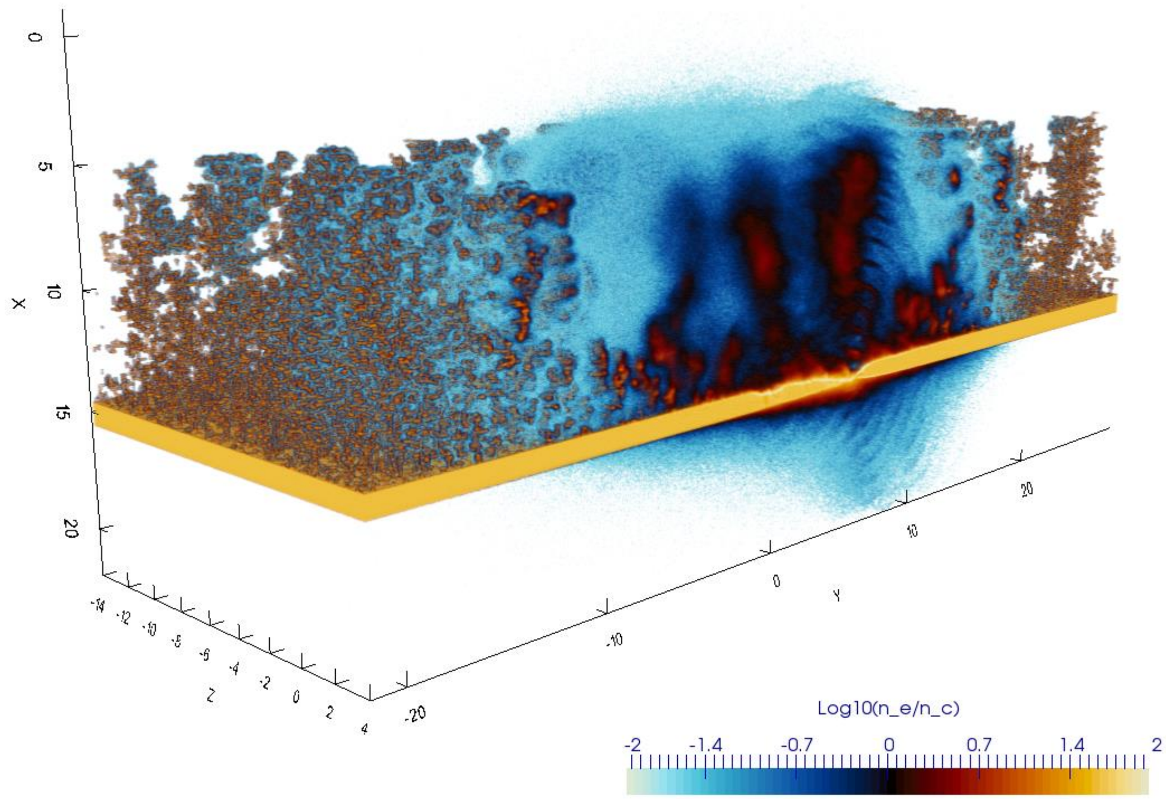
T = 28 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

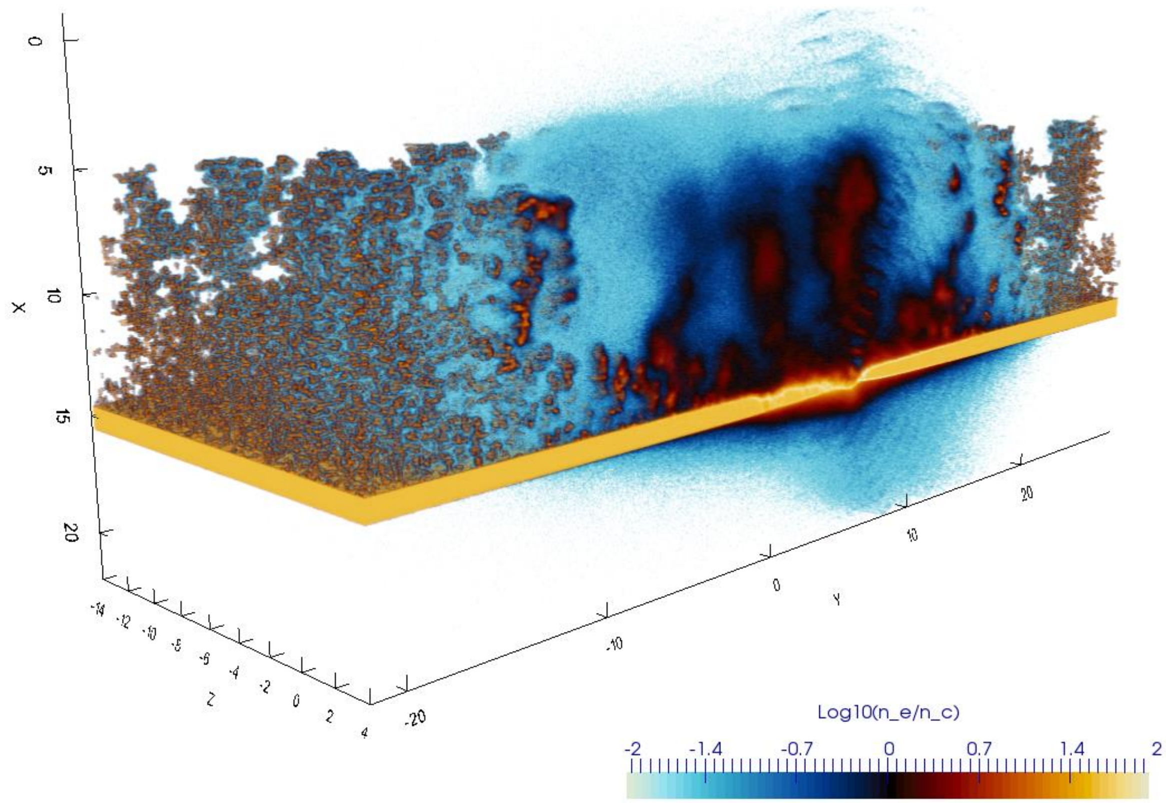
T = 32 tp



Ion acceleration with foam-based targets

Example of a 3D PIC simulation with a nanostructured foam plasma

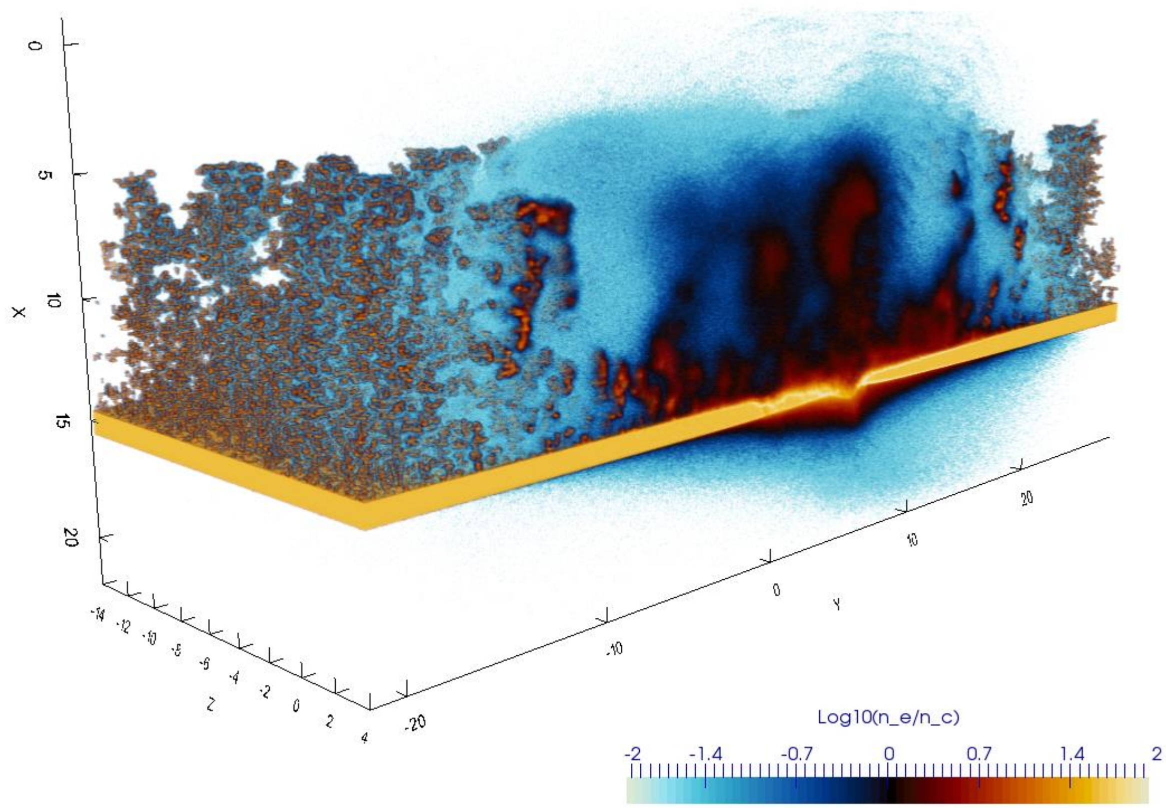
T = 36 tp



Ion acceleration with foam-based targets

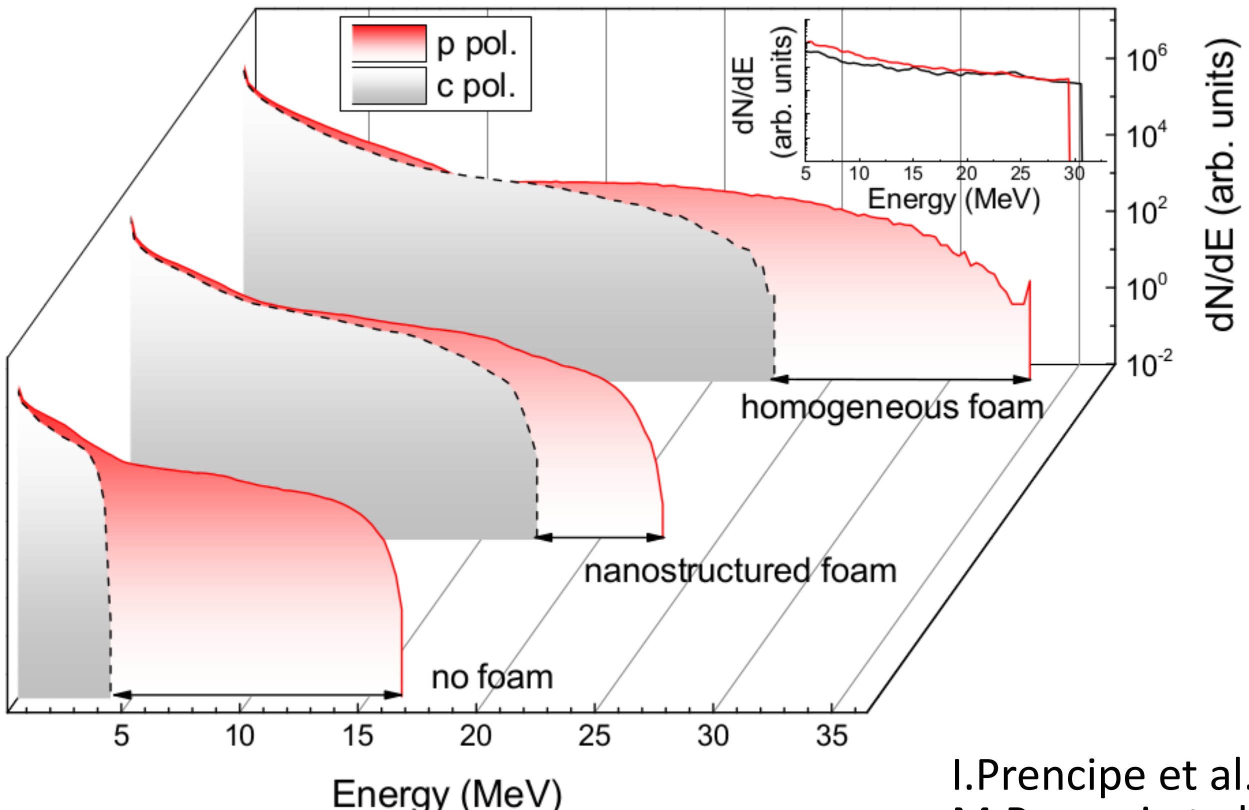
Example of a 3D PIC simulation with a nanostructured foam plasma

T = 40 tp



"Realistic" modeling based on DLA

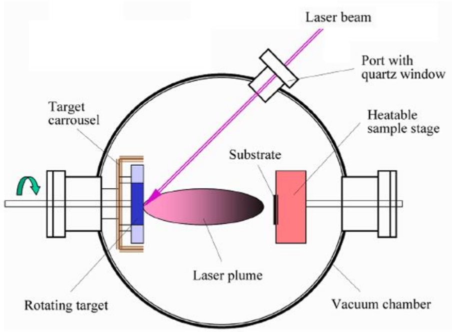
Differences in the simulated ion spectra!



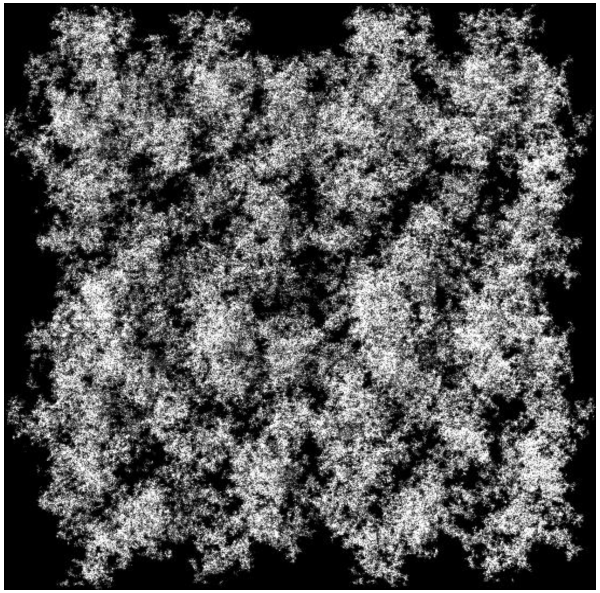
I.Prencipe et al. PPCF 58 (2016)
M.Passoni et al. PRAB 19 (2016)

An improved realistic foam model

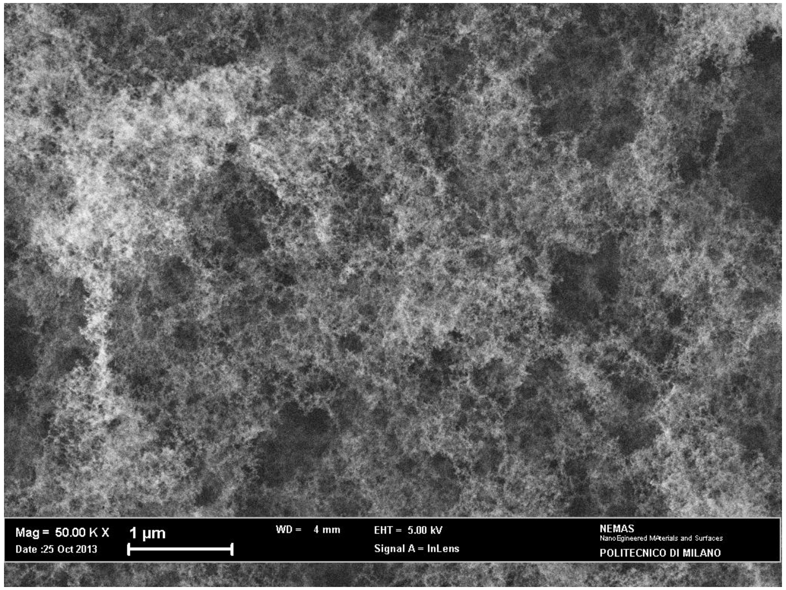
A model more closely based on the physics of Pulsed Laser Deposition…



Improved model



Real foam!

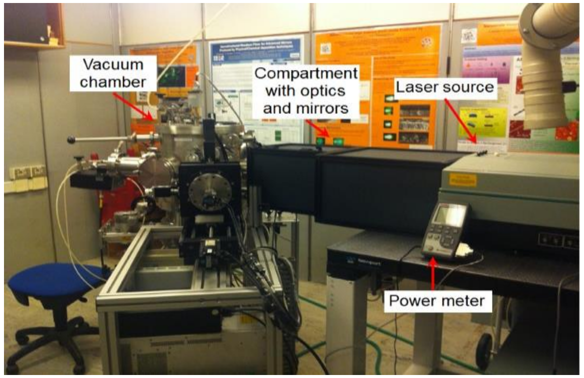


Development of advanced targets

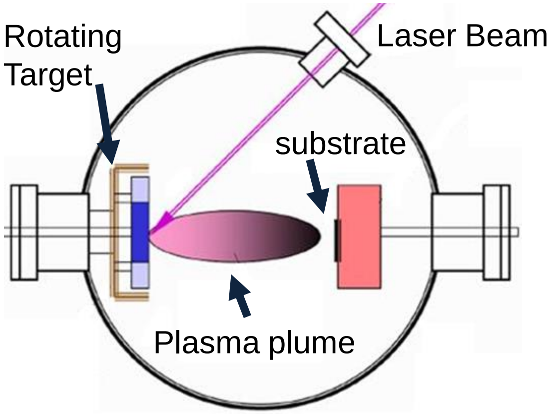
NanoLab@POLIMI facilities and infrastructures:

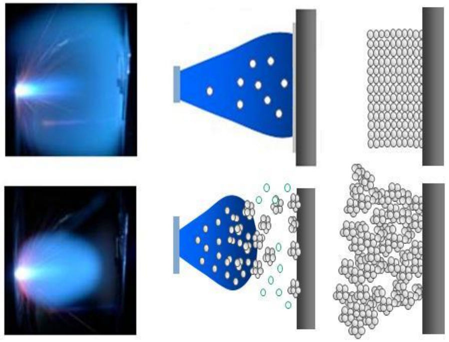
Two ns-Pulsed laser deposition (PLD) systems
Thermal treatment systems

SEM, STM, AFM microscopy
Raman & Brillouin spectroscopy

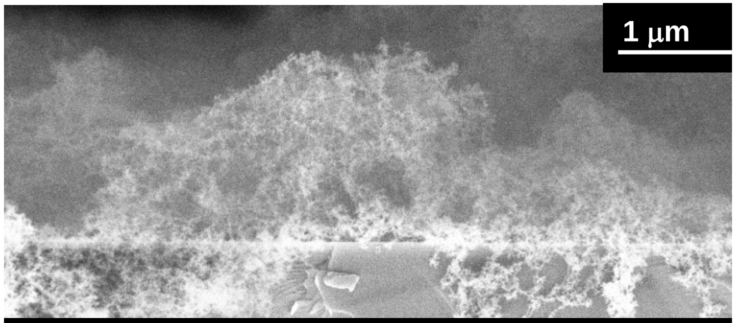


Pulsed Laser Deposition (PLD) of nanostructured targets





Carbon "foams"



Density~ mg/cm³ (between gas and solid!)

Experimental: new labs @ POLIMI!

Yesterday (2016)

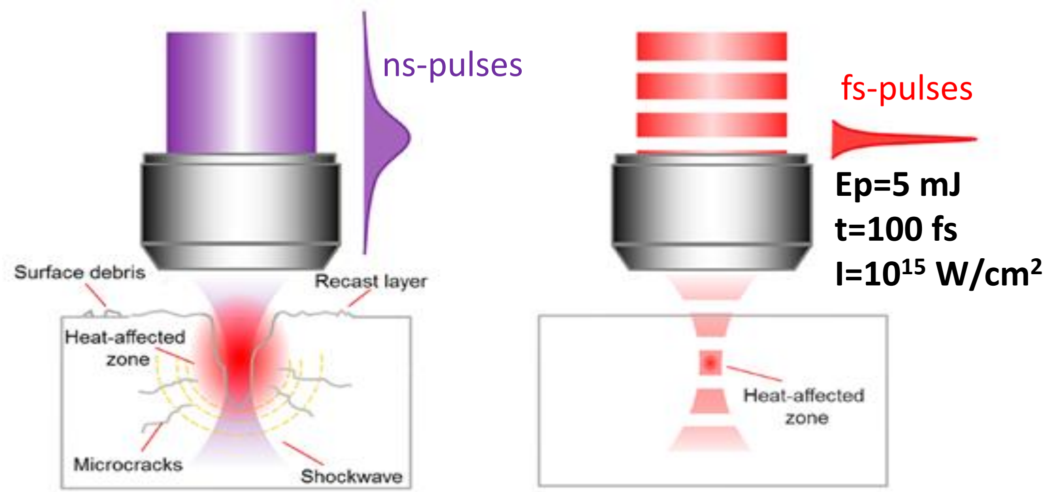
Tomorrow (within 2017)

New techniques to improve capability in **advanced target production**:

- femtosecond PLD
- HiPIMS

HiPIMS

femtosecond PLD

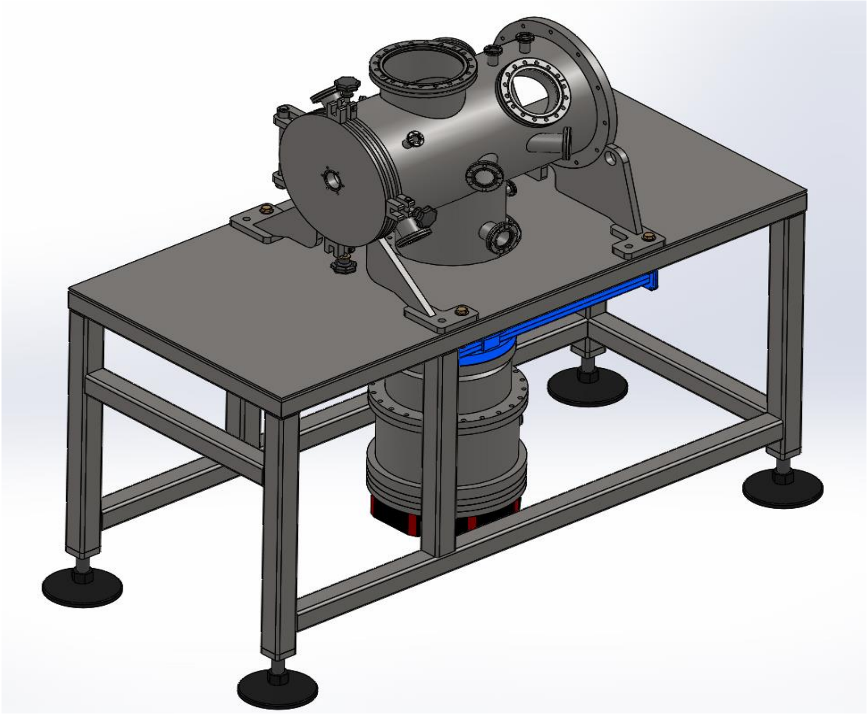


Next steps: fs-PLD under development

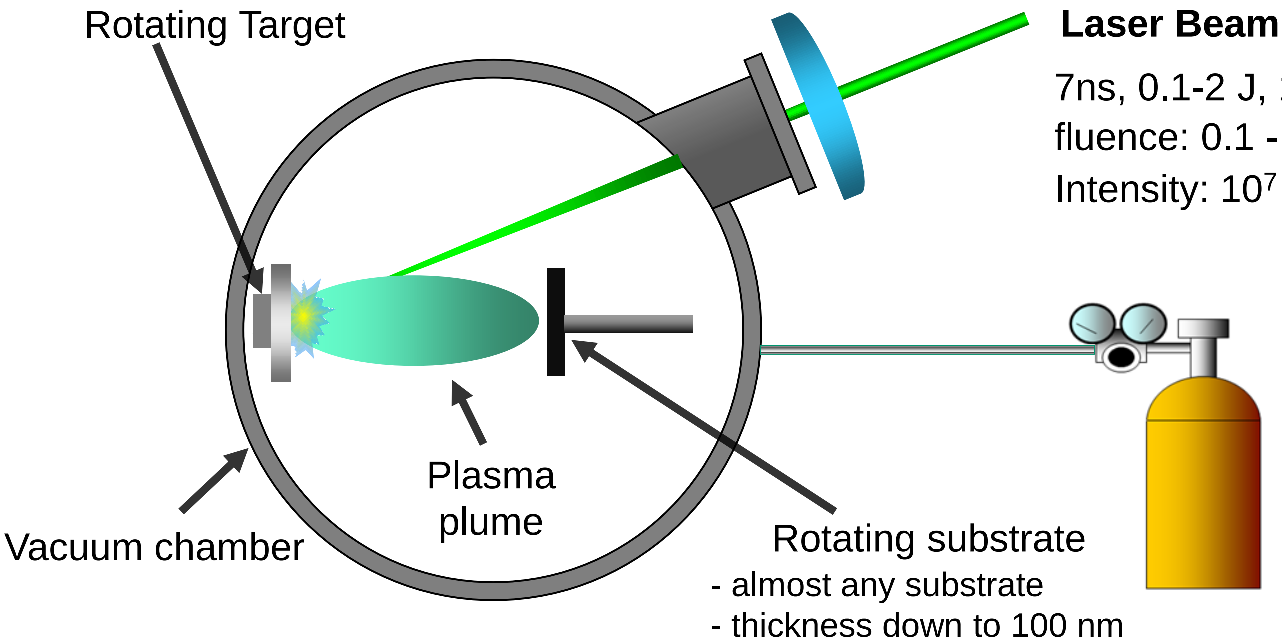
<u>Coherent “Astrella”</u>

- Tabletop laser
- τ < 100 fs
- E_p > 5 mJ

- **Femto-machining and laser processing**
- Femtosecond PLD
  - inherent production of NPs
  - New frontiers in foam production?



ns PLD in a background gas

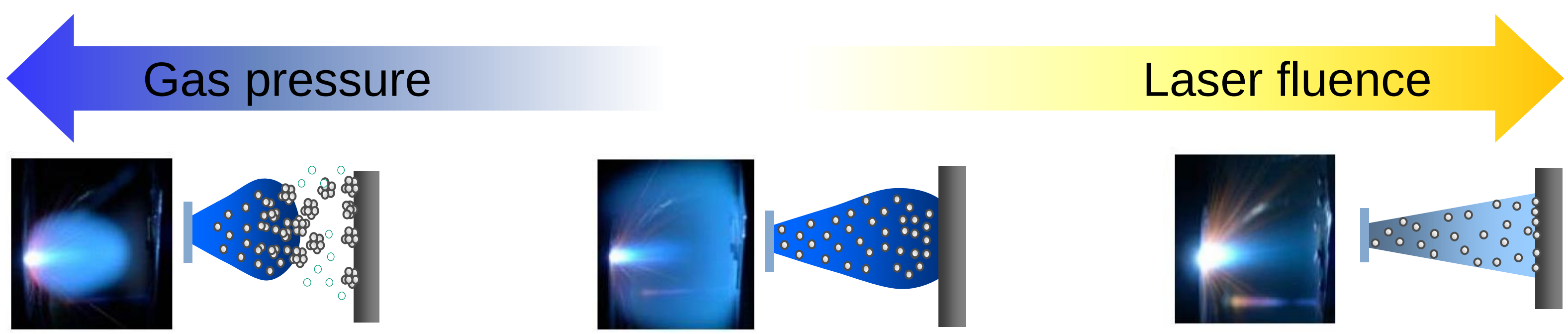


Laser Beam λ= 266, 532, 1064 nm

7ns, 0.1-2 J, 10 Hz
fluence: 0.1 - 20 J/cm^2
Intensity: 10^7 – $2x10^9$ W/cm^2

Background Gas

- Inert (He, Ar..)
- Reactive (O_2)



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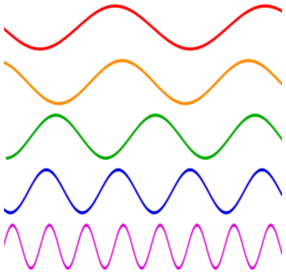
Foam property control

Nano-scale
- Crystalline structure
- Composition

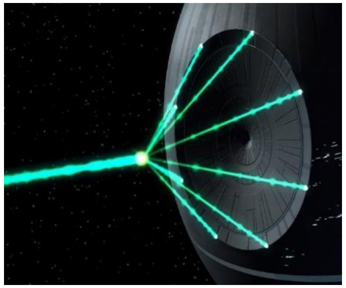
Micro-scale
- Average density
- Morphology
- ….

Macro-scale
- Uniformity
- Thickness profile

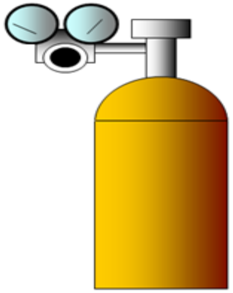
Laser Wavelength



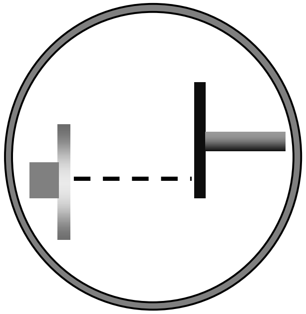
Laser Fluence



Gas pressure



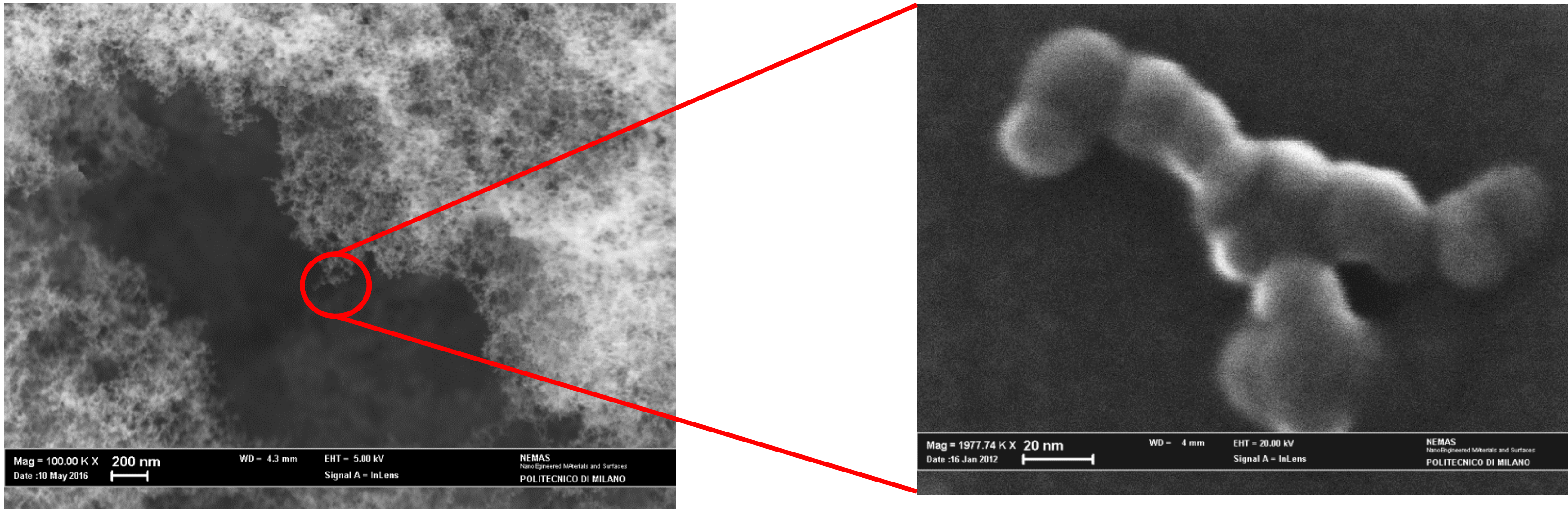
Geometry



Deposition time

PLD process parameters

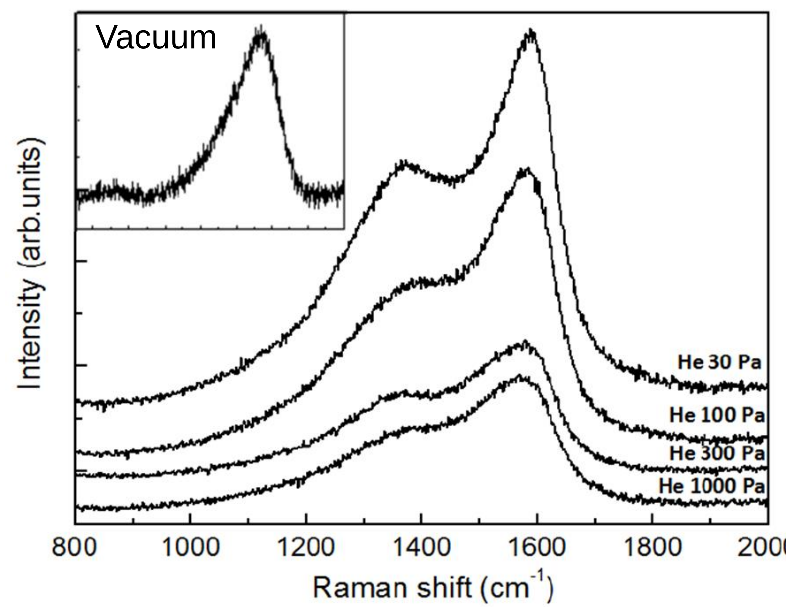
Building blocks: carbon nanoparticle



Elementary constituents:
10-20 nm nanoparticles

C-C bonding:
Nearly pure sp^2
odd-membered rings and
few chain-like structures

Crystalline structure:
Topologically disordered domains,
Size ~ 2nm



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

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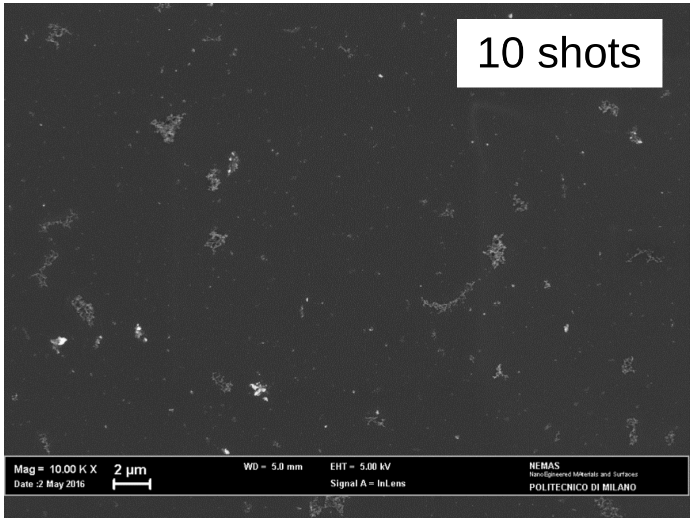
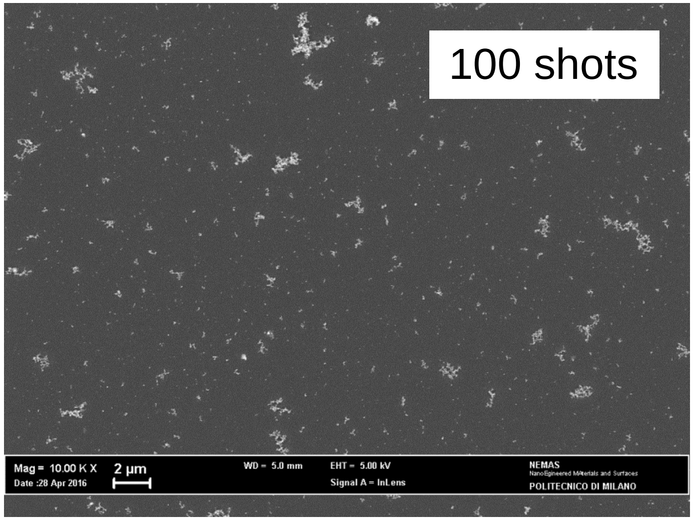
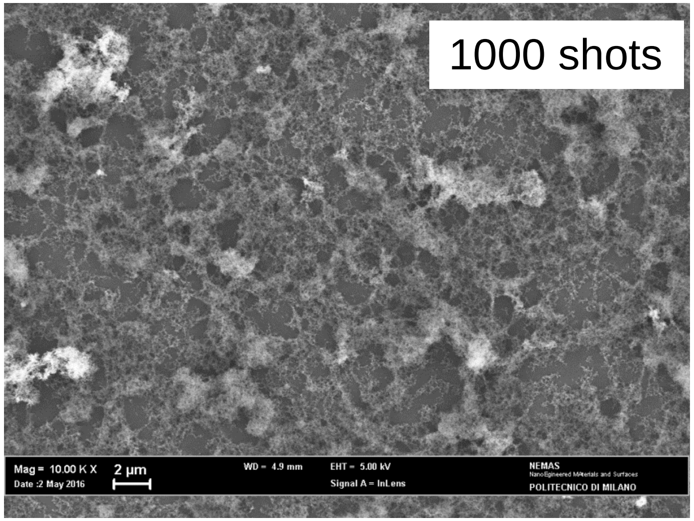
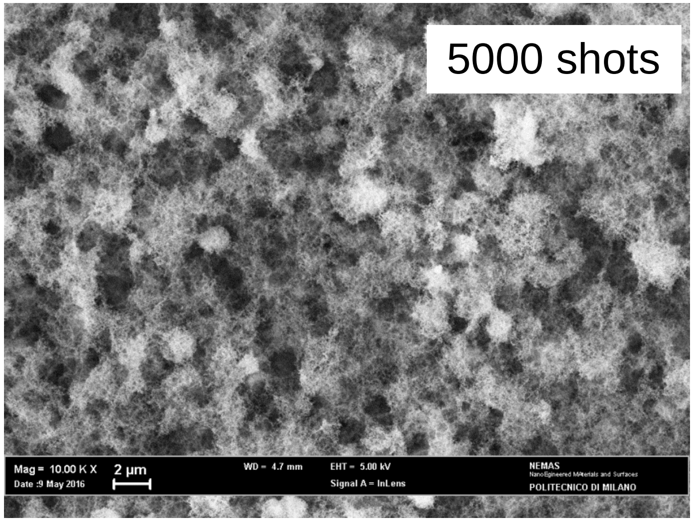
Observing the foam growth process….

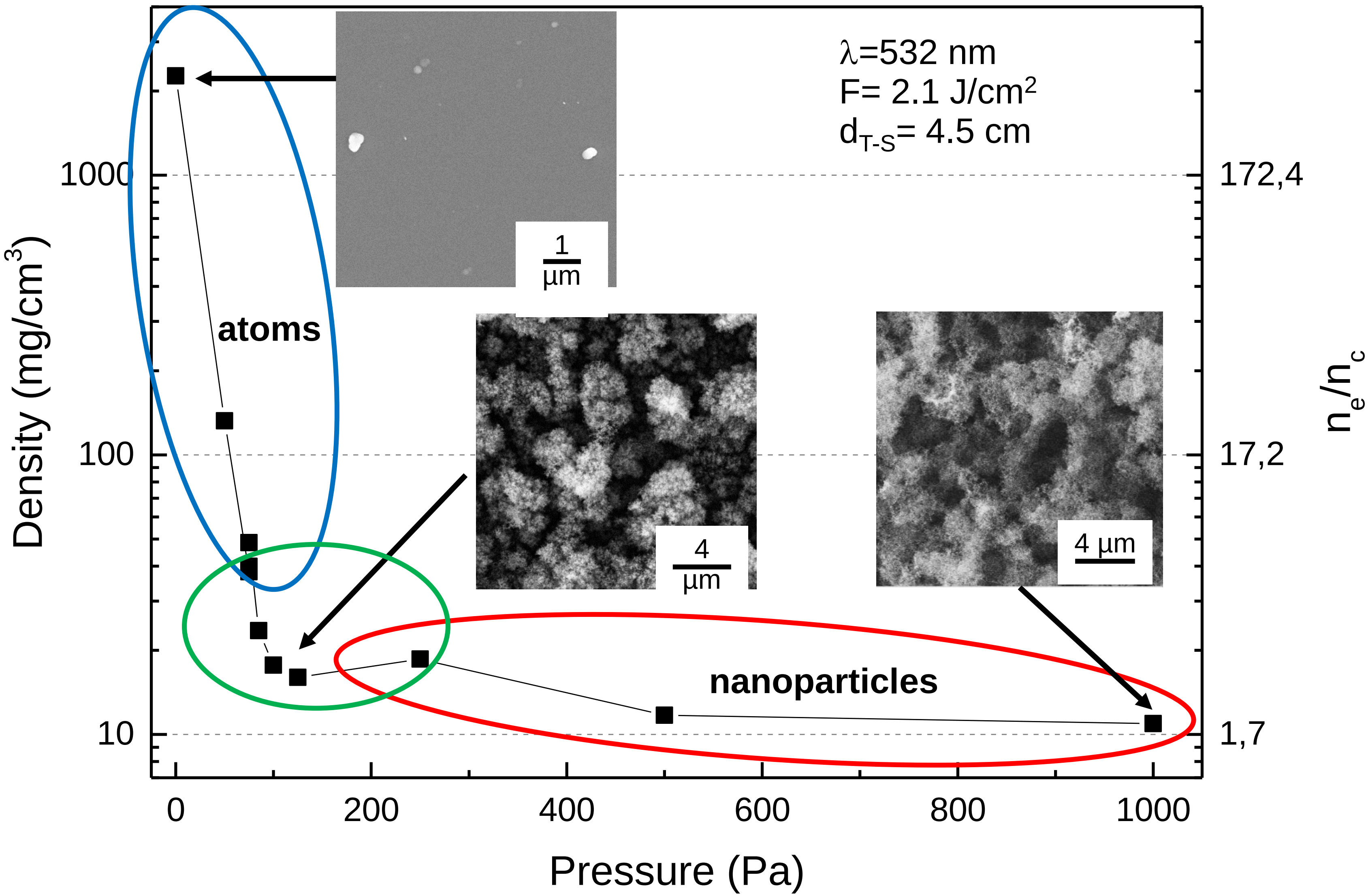








Role of process parameters - pressure

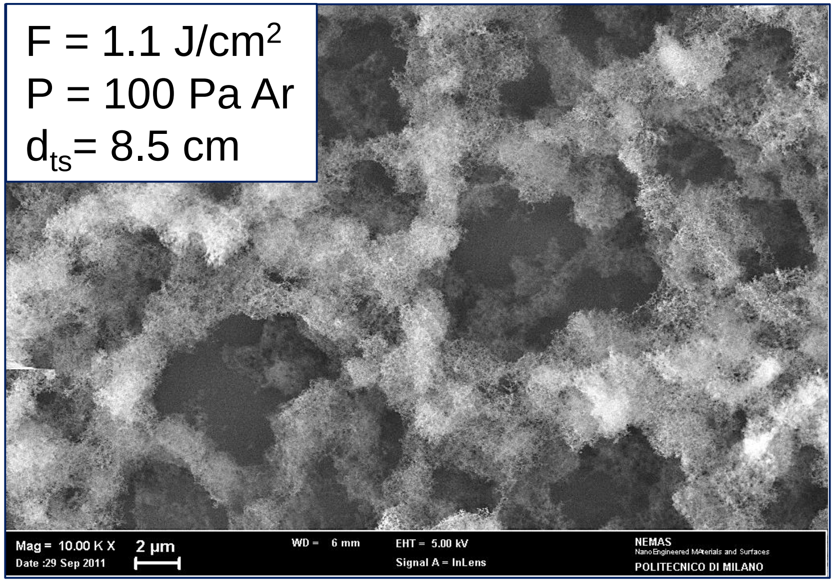


Tuning a single parameter may not be enough….

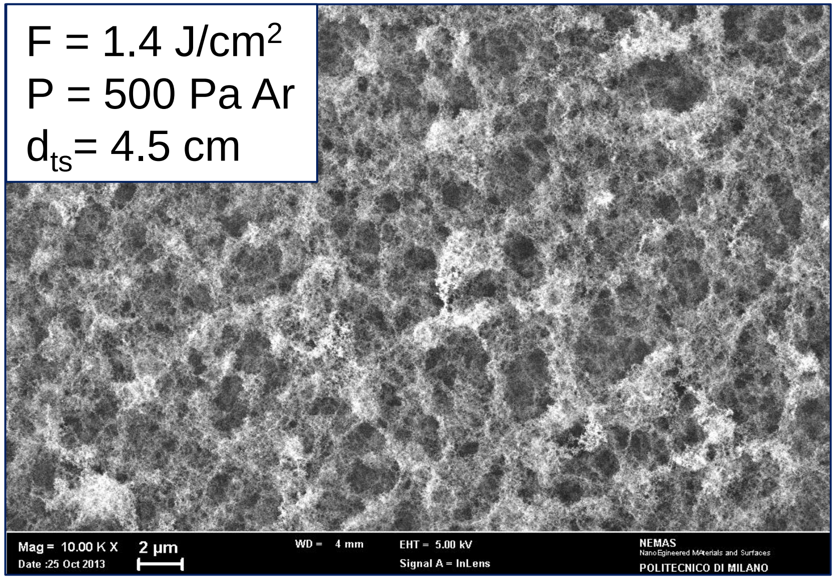
Same density = 1.5 n_c

Same thickness ≈ 8 µm

F = 1.1 J/cm^2
P = 100 Pa Ar
d_{ts}= 8.5 cm



F = 1.4 J/cm^2
P = 500 Pa Ar
d_{ts}= 4.5 cm



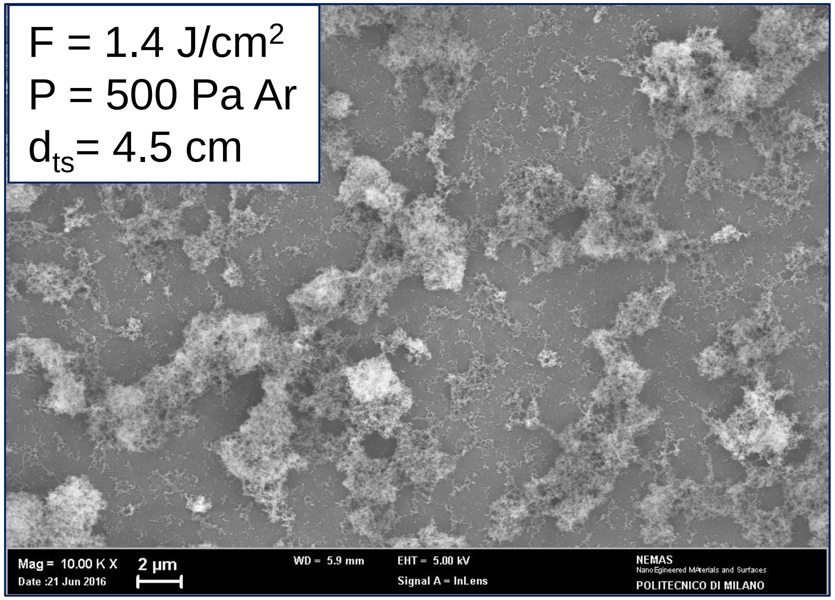
- F = 1.1 J/cm^2
- P = 100 Pa Ar
- d_{ts}= 8.5 cm

- F = 1.4 J/cm^2
- P = 500 Pa Ar
- d_{ts}= 4.5 cm

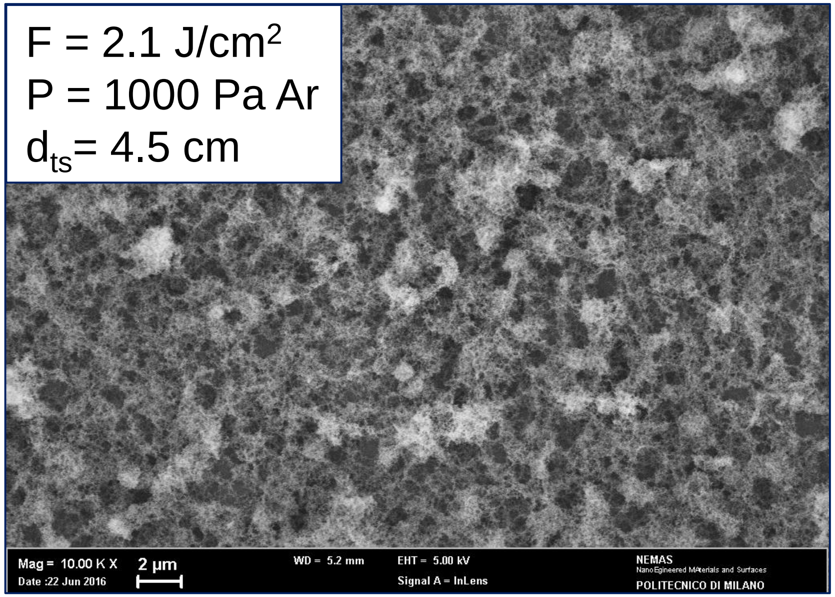
Better uniformity & coverage!

Towards "thinner" foams…

Nominal thickness ≈ 4 μm



Nominal thickness ≈ 4 μm



1) Decreasing deposition time might not be enough!

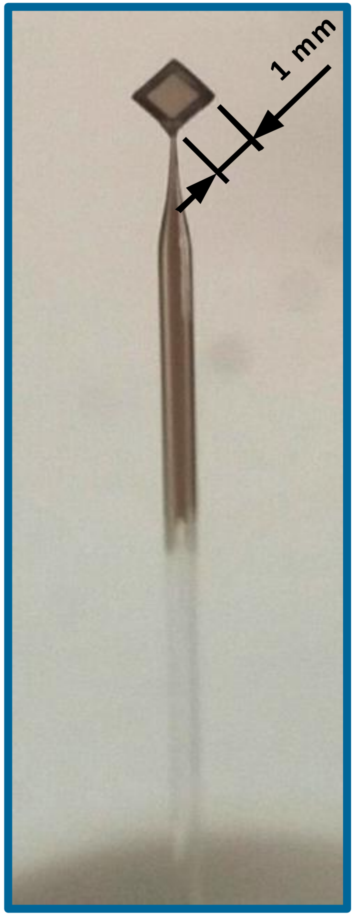
2) Understanding foam grow vs process parameters is crucial

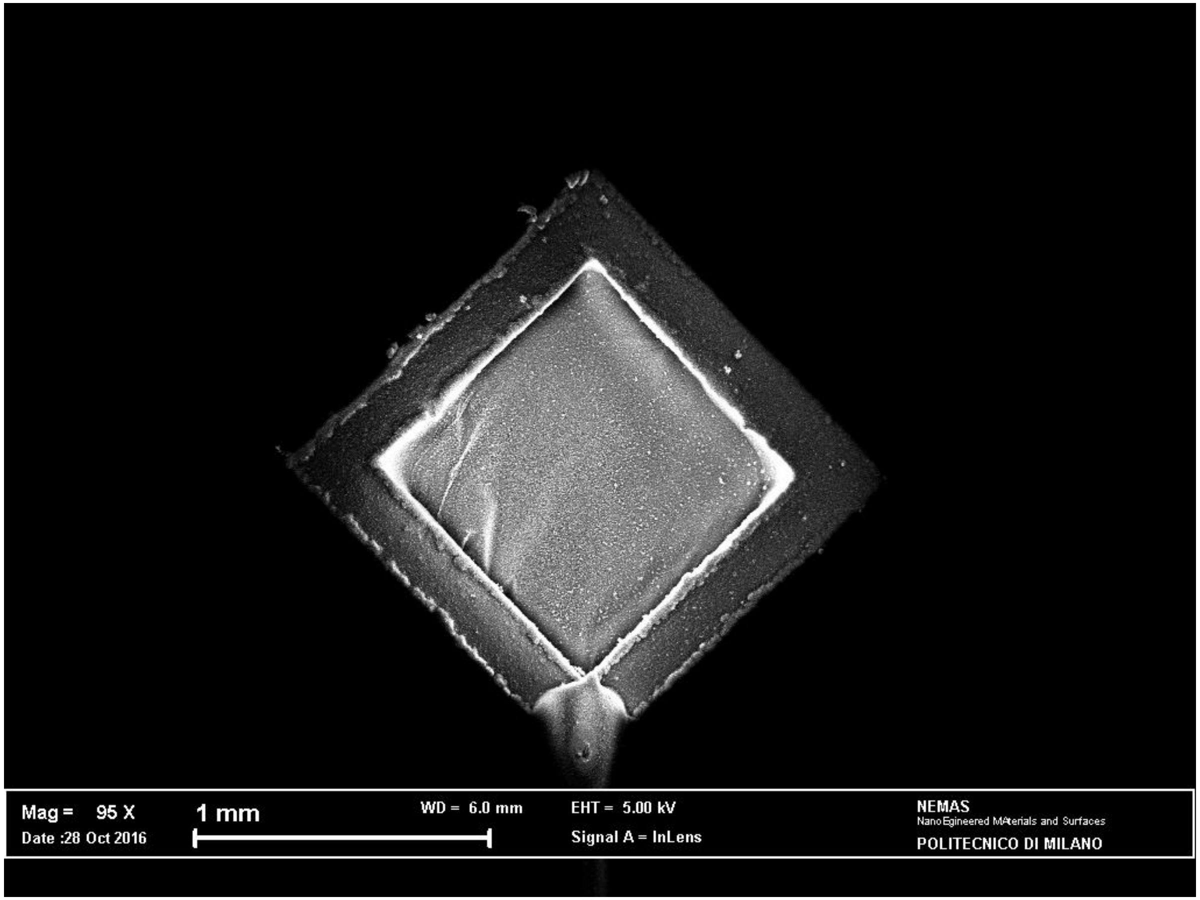
New multilayer target development

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

in collaboration with:
A. Morace

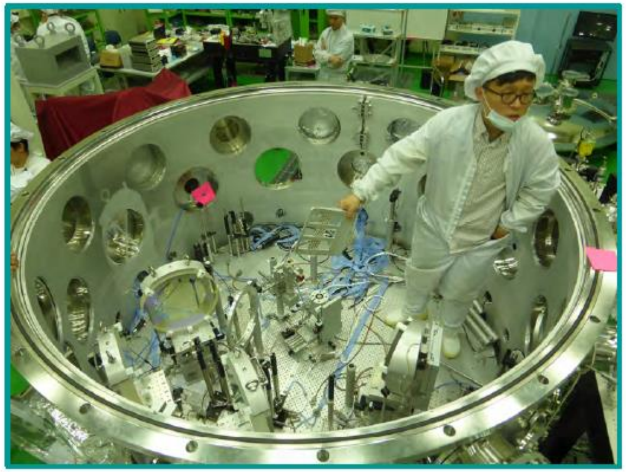
OSAKA UNIVERSITY

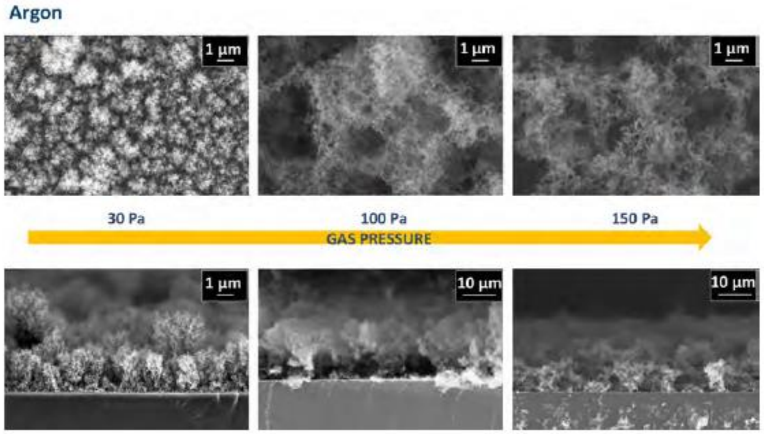


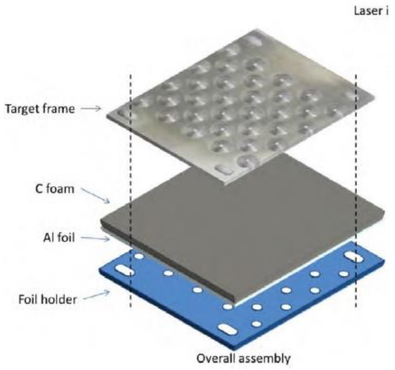


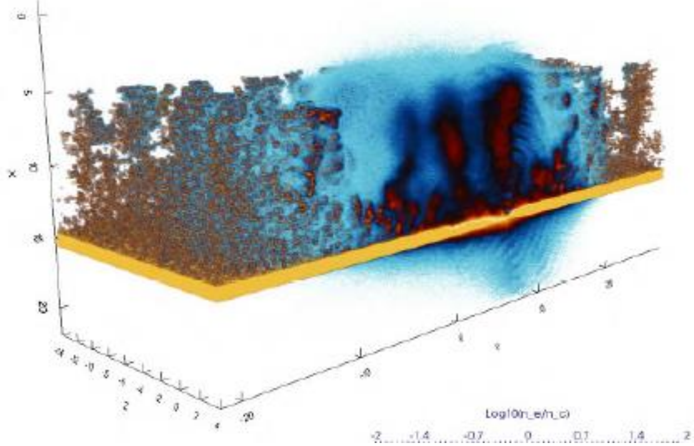
Ion acceleration with foam-based targets

Target preparation, experiments on laser facilities and simulations





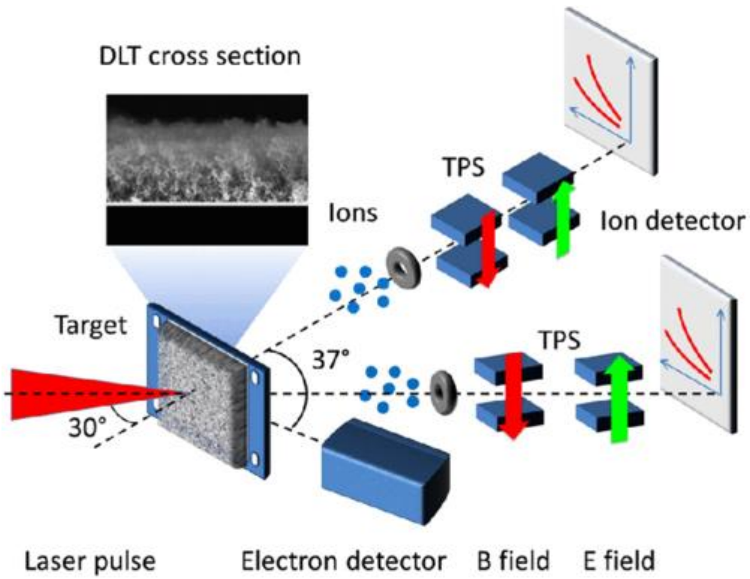




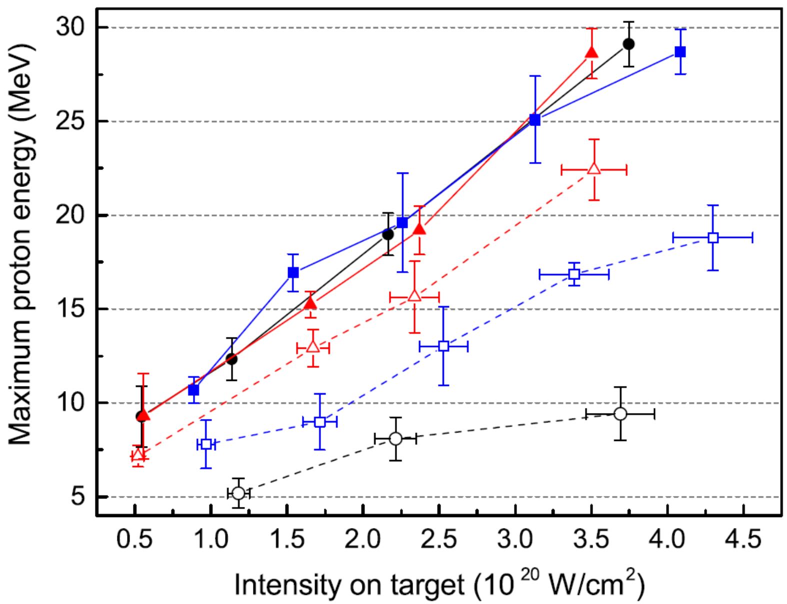
Experiments on laser facilities

Ion acceleration experiments:
- Performed at **GIST** (Rep. of Korea) in 2015-2016
- Performed at **HZDR** (Germany) in 2017
- Performed at **ILE** (Osaka) in 2017

Setup of an ion acceleration experiment:



Effects of advanced targets:



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)

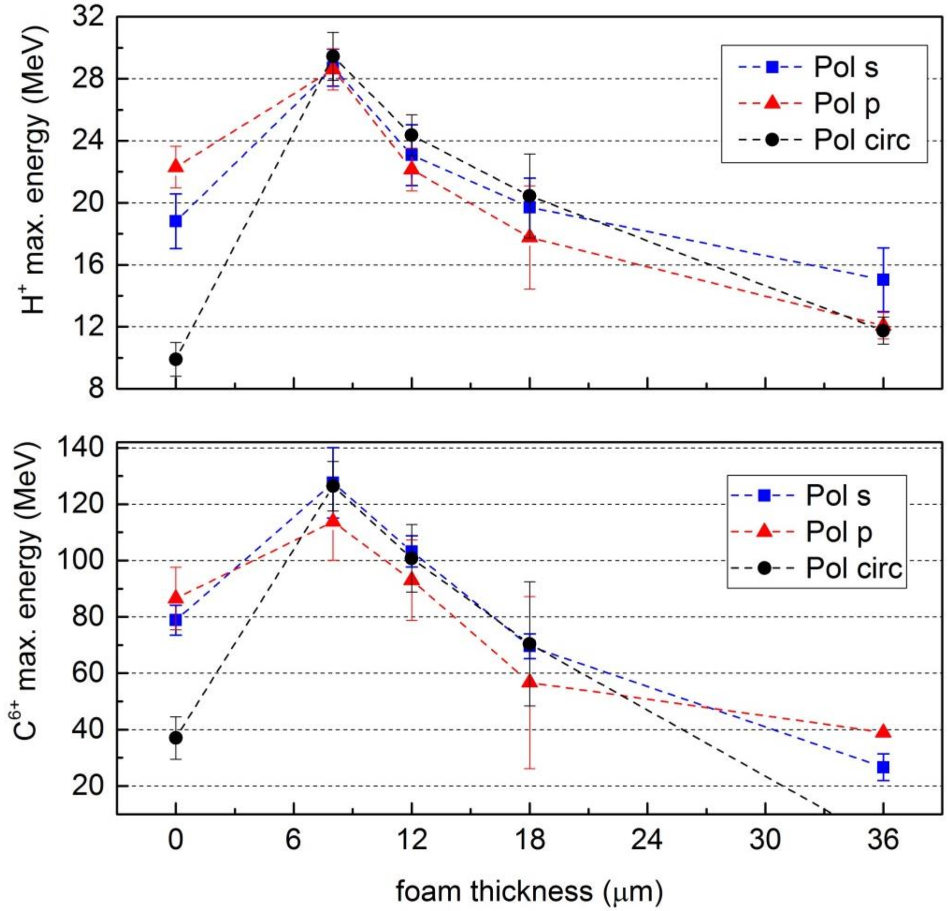
in collaboration with:
I. W. Choi, C. H. Nam et al.

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

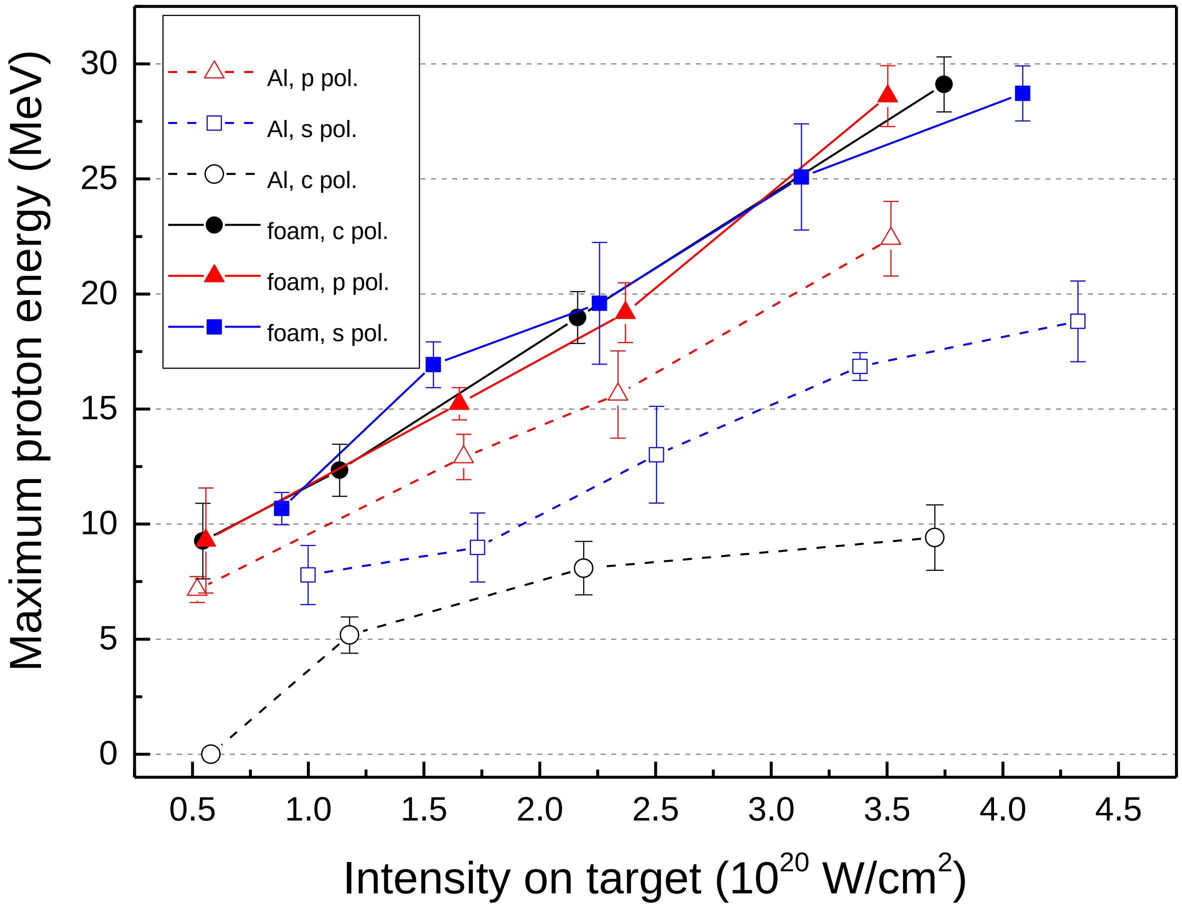
- Energy on target = 8 J
- Intensity = 0.5 10^{20} - 5 10^{20} W/cm^2
- Angle of incidence = 30°



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)

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Ion acceleration @ DRACO 150 TW

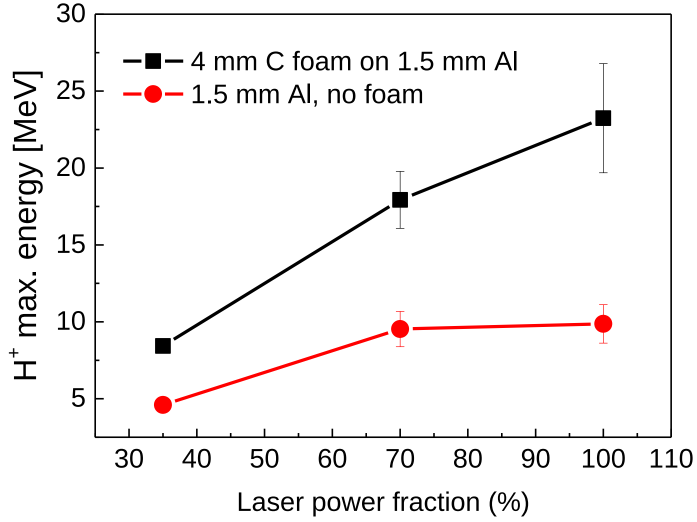
(preliminary data!)

HZDR

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

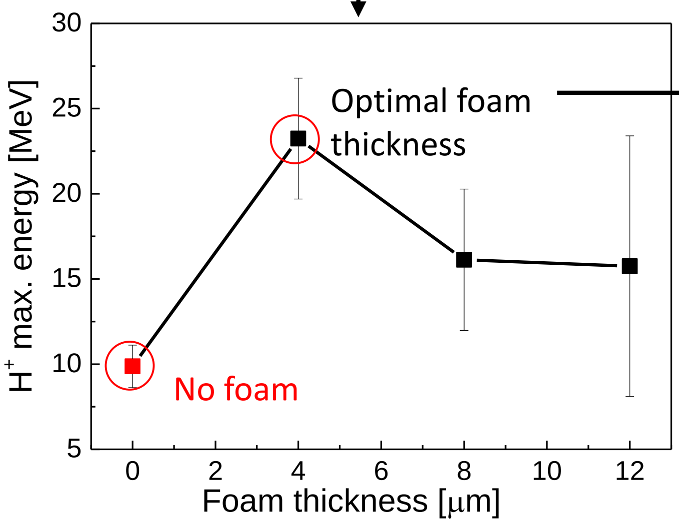
Laser parameters @ Draco (HZDR, Dresden)

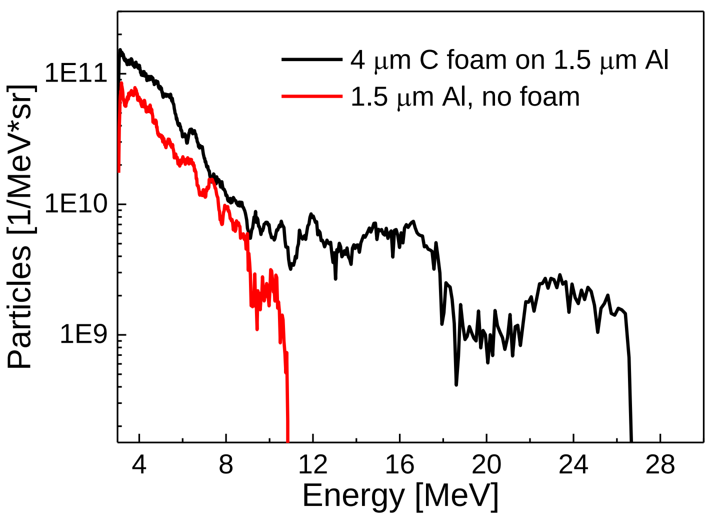
- Energy on target = 2 J
- Intensity = up to 5 x 10^{20} W/cm^2
- Angle of incidence = 2°



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

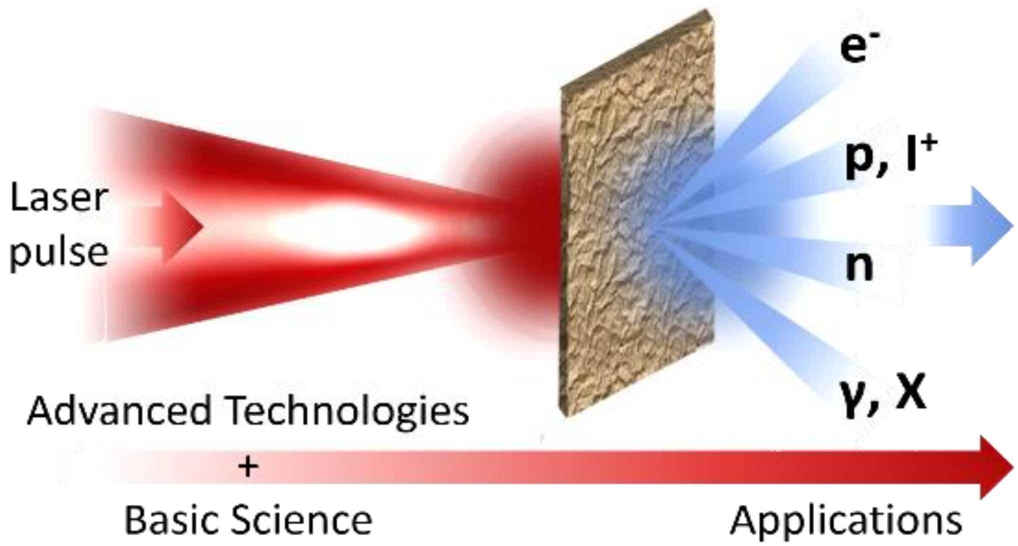


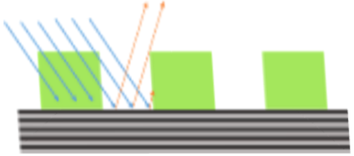


An example of application:

Material characterization & processing with laser-driven ion beams

- Ion beam analysis: RBS, NRA, PIXE,…
- Neutron imaging and radiography….
- Ion implantation
- Radiation damaging…





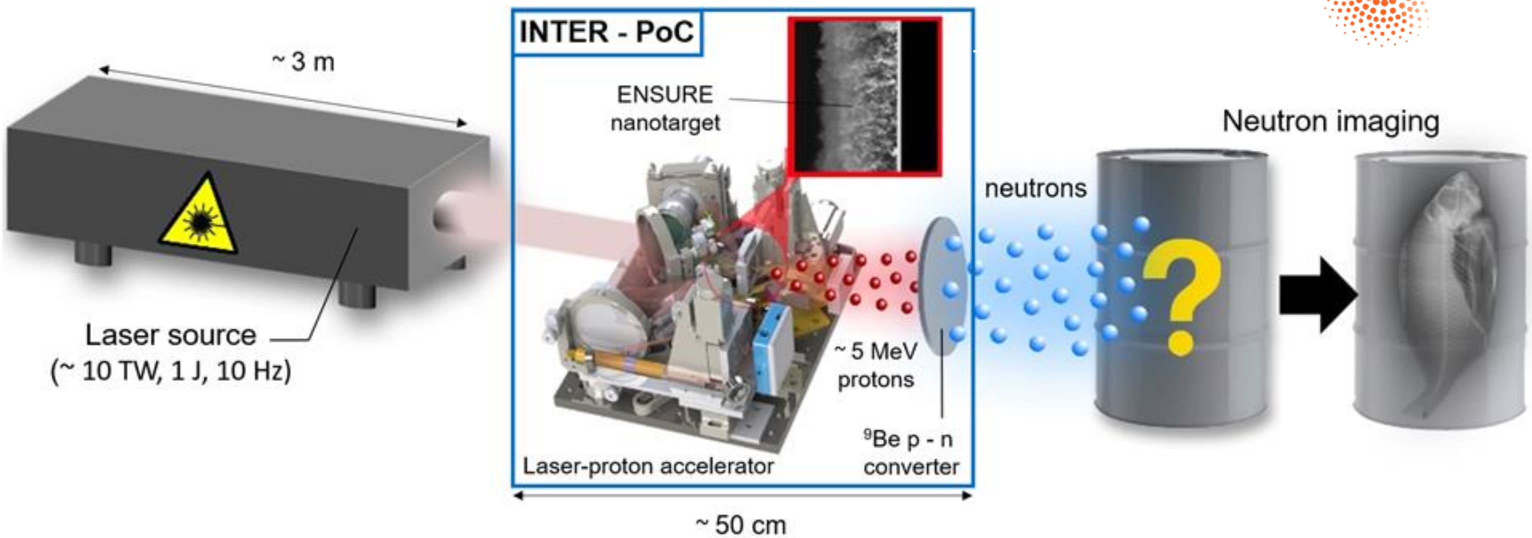
Laser-driven ion beams may *ensure* major advantages!

F. Mirani, Master thesis in Nuclear Engineering (2017)

Another example of application:

Towards a portable neutron source

ERC-PoC: **INTER**



Queen's University Belfast — 2017/2018 : pulsed neutron generation

SourceLAB — ERC-PoC: **INTER** — 2017/2018 : compact ion and neutron sources for materials characterization

Conclusions

- **Nanostructured foams** are **one of the few ways to obtain a controlled near-critical plasma**
- simulations to understand **how this affects laser-nanostructured plasma interaction;** nanostructure may **affect experimental observables**
- Production of **multilayers targets** composed of near critical carbon foam 4 um thick
- Promising results in **laser-ion acceleration experiments**
- Laser-ions can be interesting in **materials and nuclear sciences**

Thanks for your attention!

ENSURE

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

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