CMD30
FisMat 2023

joint conference
Milano - September 4-8, 2023

Mini-colloquium: Italian Plasma Physics

# Theoretical investigations of laser-plasma interaction with low-density nanostructured targets at PoliMi

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

# Outline

- Laser-Plasma Interaction and Numerical Methods
- Advanced Near-Critical Targets
- Relevant Physics in Advanced Targets
- Ion Acceleration
- High-energy Photons
- Other radiations

# Ultra-intense Laser-Plasma Interaction

Interesting for Acceleration/Generation of electrons, ions, photons, neutrons, positrons, …

- 10s fs duration
- focal spot of μm
- $I > 10^{18}$ W/cm$^2$

$$a_0 = \frac{eE_0}{m_e \omega c} > 1$$

Normalized Vector Potential

$$n_c = \frac{m_e \omega^2}{4\pi e^2}$$

Critical Electron Density

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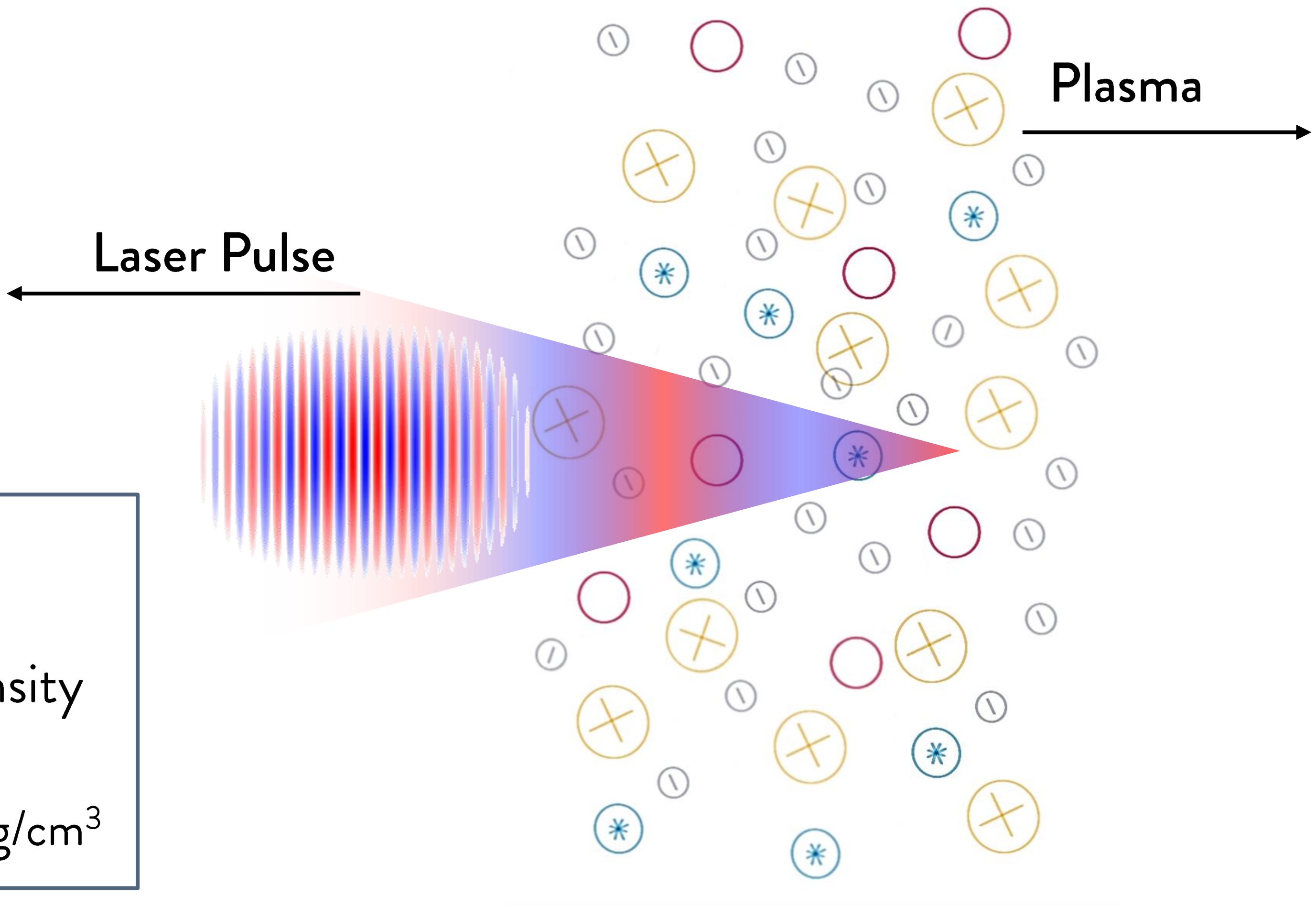
Target Density of few mg/cm$^3$

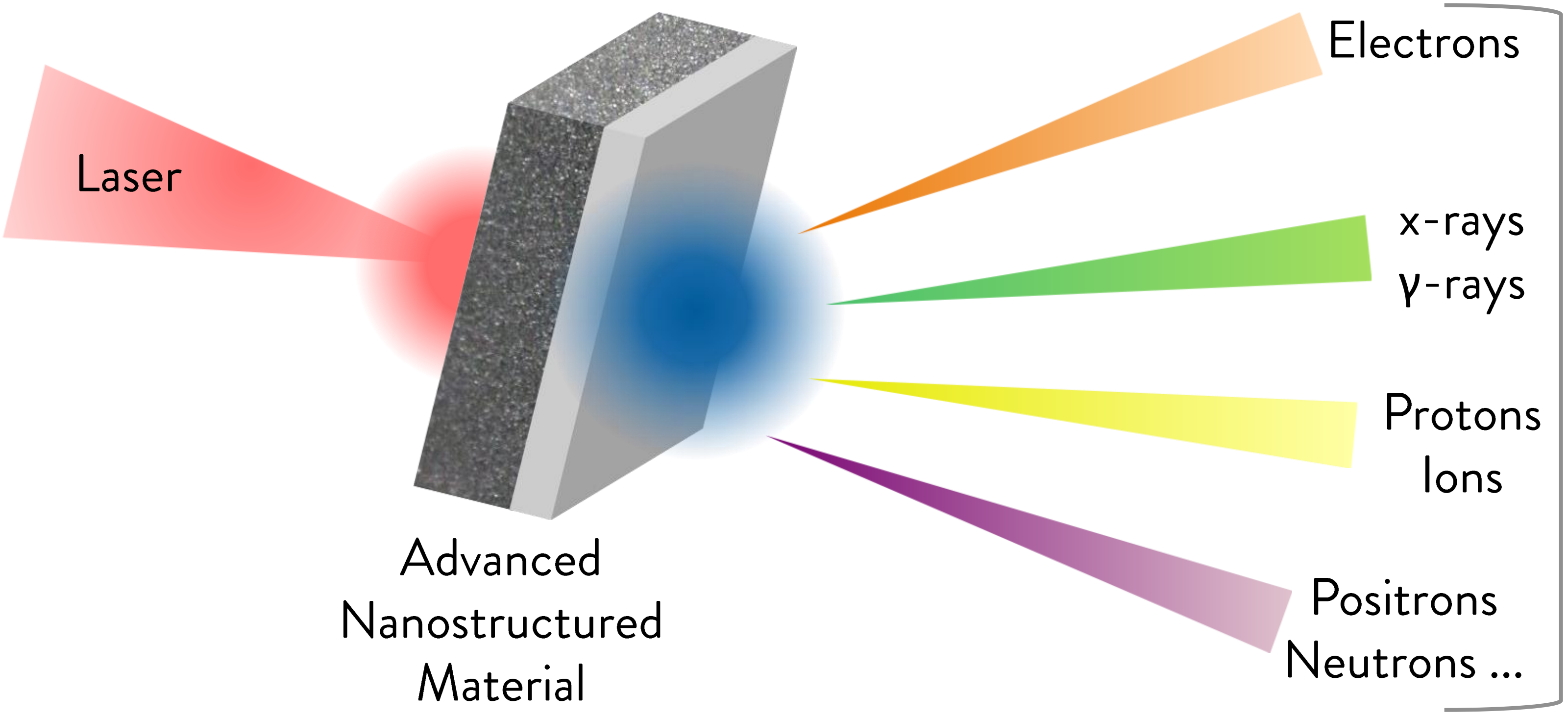



From target ionization

Different regimes of interaction:

- Gas $n_e \ll n_c$
- Near-critical $n_e \simeq n_c$
- Solid $n_e \gg n_c$

# Motivations




Multipurpose Tunable Laser-Driven Radiation Source

Advantages: compactness, ultrafast duration, small source size, high energy and high flux

Possibly exploiting table-top laser systems (TW or less)


Enabling Tools

- **Theoretical and Computational Plasma Physics**
- Laser and Material Sciences and Technologies
- …

Design, Perform and Interpret Experiments

Design of Applications

- Proton-Induced X-ray Emission (PIXE) (See poster by **Francesco Mirani**)
- Radiography and Tomography
- And many more…

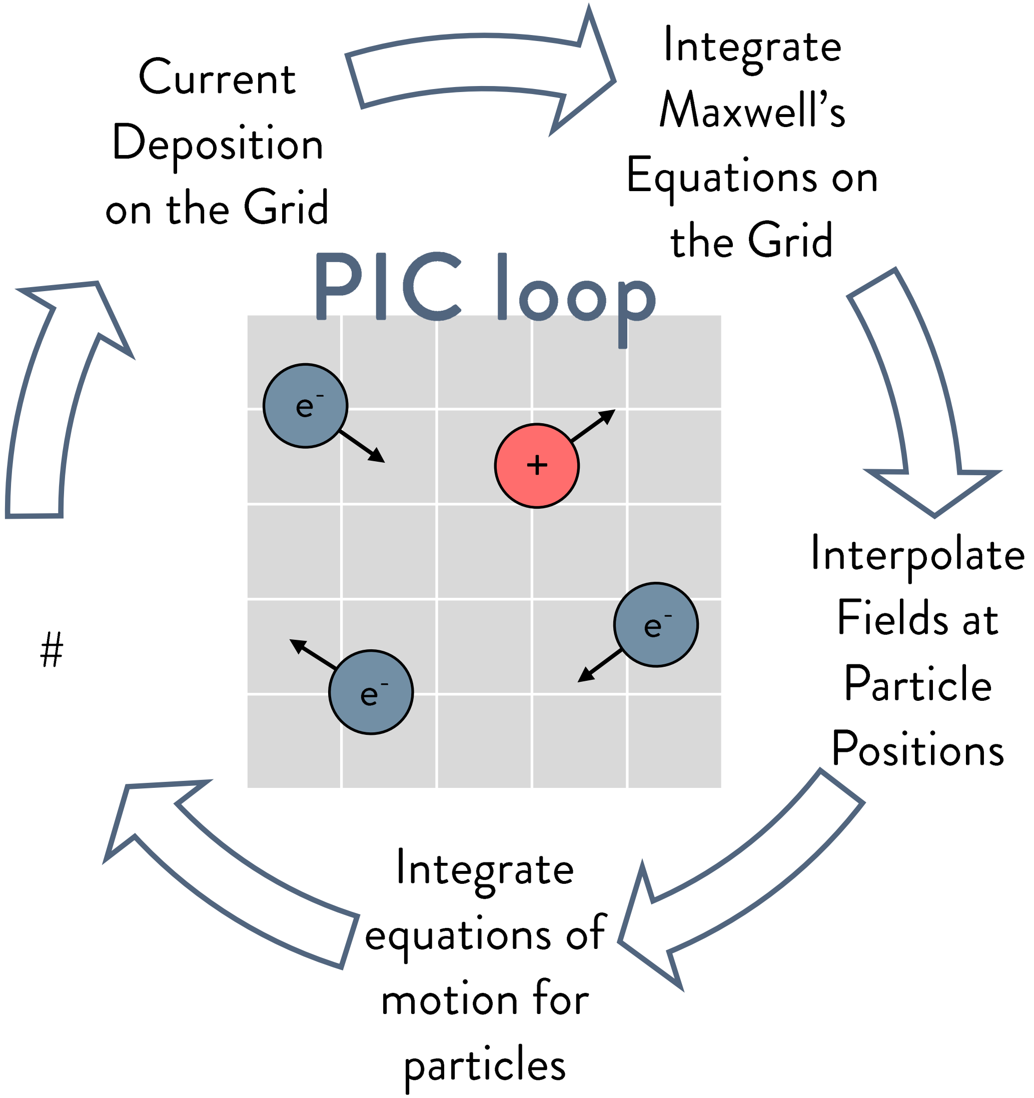
# Particle-in-cell (PIC) Simulations

Approximately solve the **kinetic collisionless relativistic Vlasov-Maxwell system.**

Sampling of the distribution functions with macro-particles:

$$f_a(\mathbf{x},\mathbf{p},t) \approx \sum_{p=1}^{N_a} S(\mathbf{x}-\mathbf{x}_{pa}(t))\delta(\mathbf{p}-\mathbf{p}_{pa}(t))$$

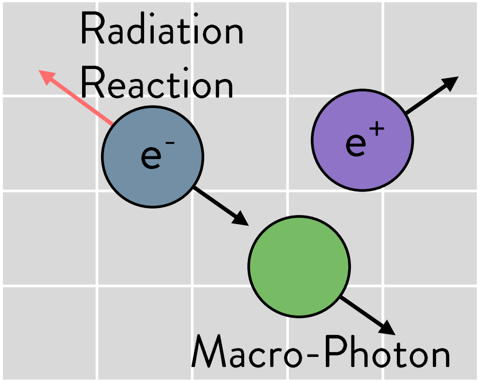
- **Macro-particles** follow the relativistic equations of motion.
- **Electromagnetic fields** computed on a discrete grid in space with Maxwell equations.
- # **other physics** may be included: collisions, ionization, photon emission, …



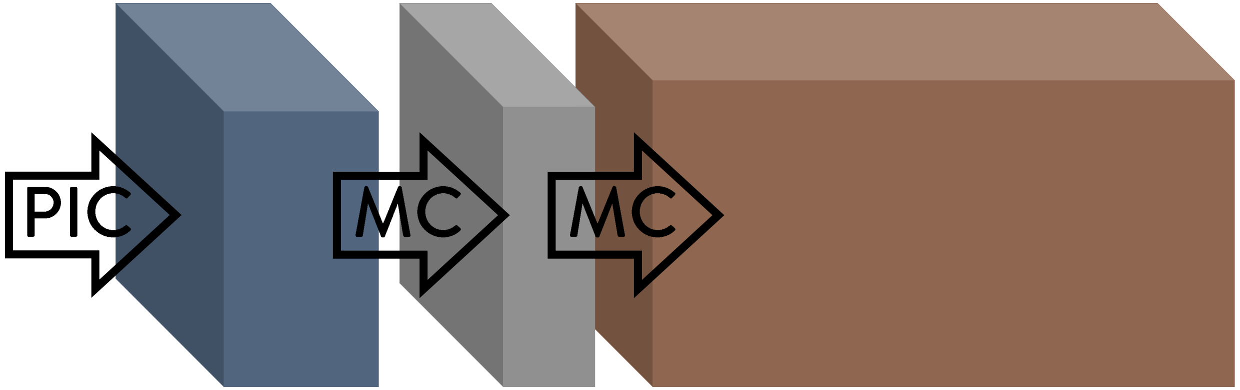
# Monte Carlo Approaches

Evaluation of additional physics and secondary particle generation.

- **Extended PIC** with a **Monte Carlo step** to evaluate collisions, field ionization, photon emission, pair production, nuclear reactions, …
  - Consistent with the plasma environment.
  - New macro-particles can be generated.
  - Computationally expensive.



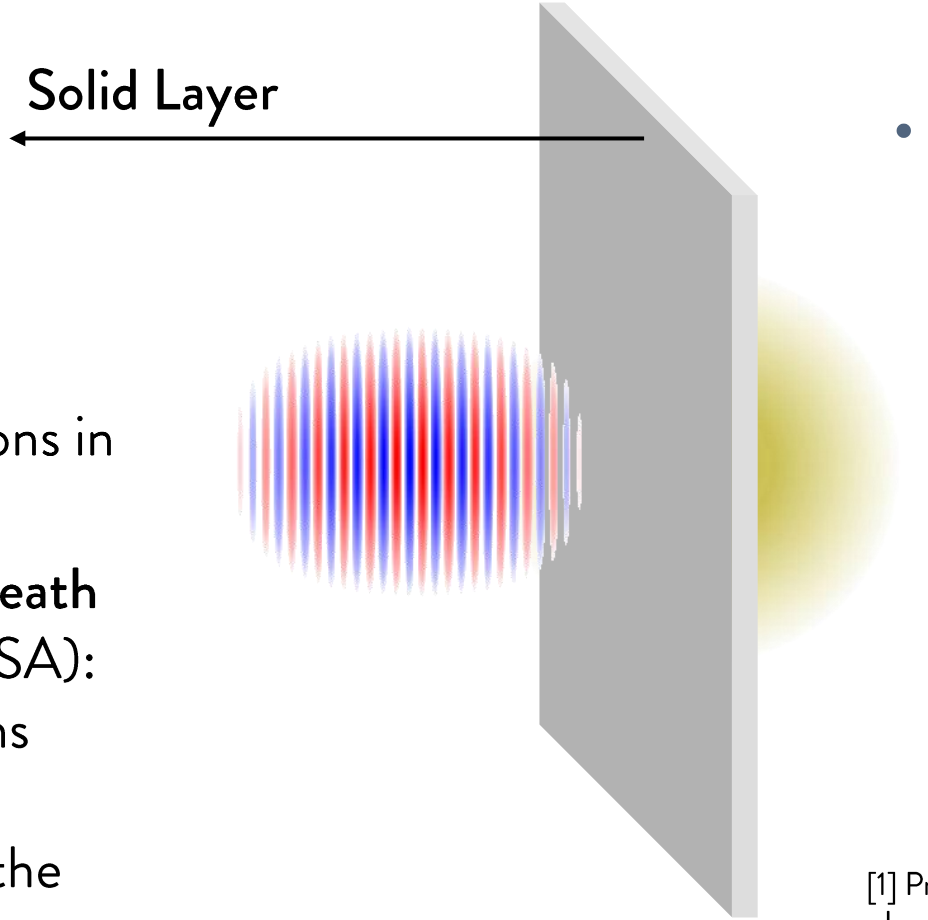

- Feed a **standard Monte Carlo** transport code with particle properties from PIC.




- Passage of particles in neutral matter.
- Thick and dense targets → Yes!

# Advanced Targets for Particle Acceleration/Generation

- Solid density
- μm thickness




- Heating of electrons in the solid layer
- **Target Normal Sheath Acceleration** (TNSA): 1-10s MeV Protons from low-mass contaminants on the rear side

- Standard for Laser-Driven Ion Acceleration
- But can we enhance and tune the coupling with the laser pulse and efficiently exploit compact lasers? Yes!

↓

**Advanced Targets** from advanced material deposition techniques

<u>See posters by **Francesco Mirani** and **Davide Vavassori** for details on target production and deposition techniques</u>

Fedeli, L., Formenti, A., Cialfi, L., Sgattoni, A., Cantono, G., & Passoni, M. (2017). Structured targets for advanced laser-driven sources. Plasma Phys. Control. Fusion, 60(1), 014013.

[1] Prencipe, I., Sgattoni, A., Dellasega, D., Fedeli, L., Cialfi, L., Choi, I. W., Kim, I. J., Janulewicz, K. A., Kakolee, K. F., Lee, H. W., Sung, J. H., Lee, S. K., Nam, C. H., & Passoni, M. (2016). Development of foam-based layered targets for laser-driven ion beam production. Plasma Phys. Control. Fusion 58(3), 034019.

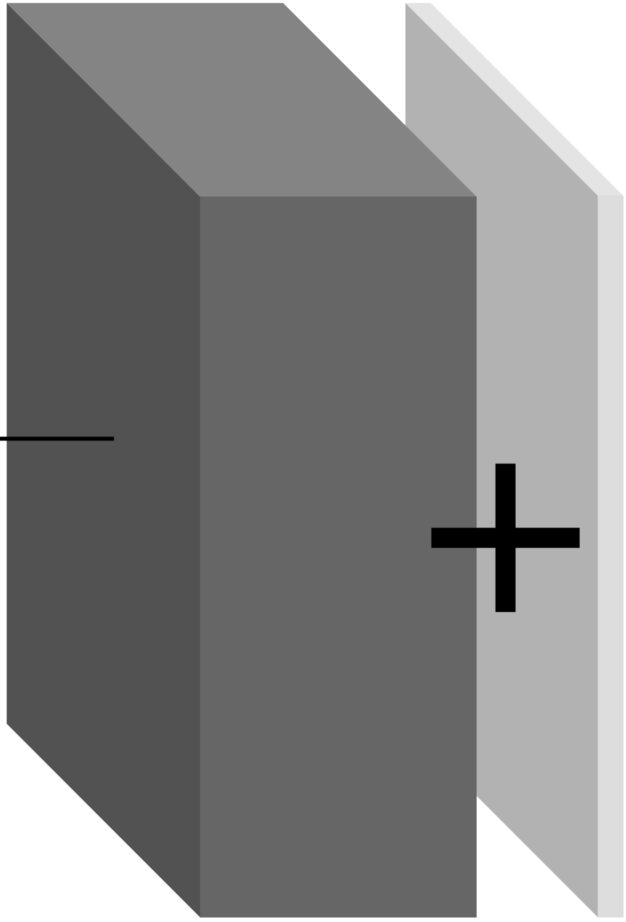
# Advanced Targets for Particle Acceleration/Generation

- Near-critical density

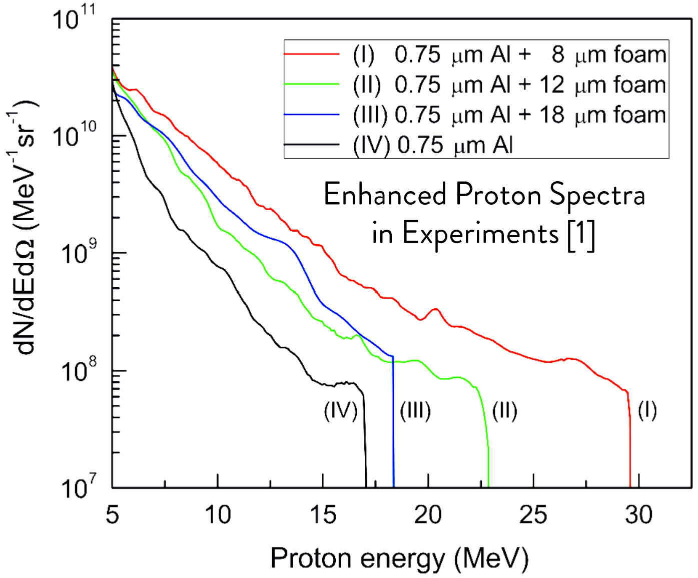
$$n_c = \frac{m_e \omega^2}{4\pi e^2}$$

- 1-10s μm thickness

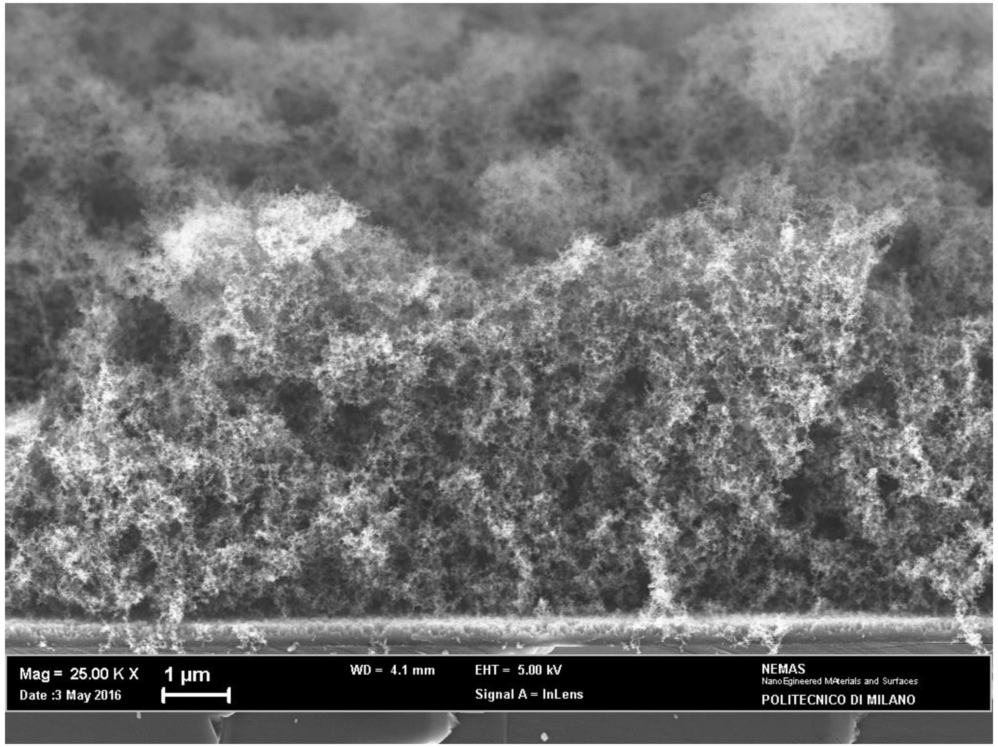
Low-density Layer



Double-Layer Target (DLT)




Nanostructured Carbon Foam




Produced with **Pulsed Laser Deposition** (PLD)

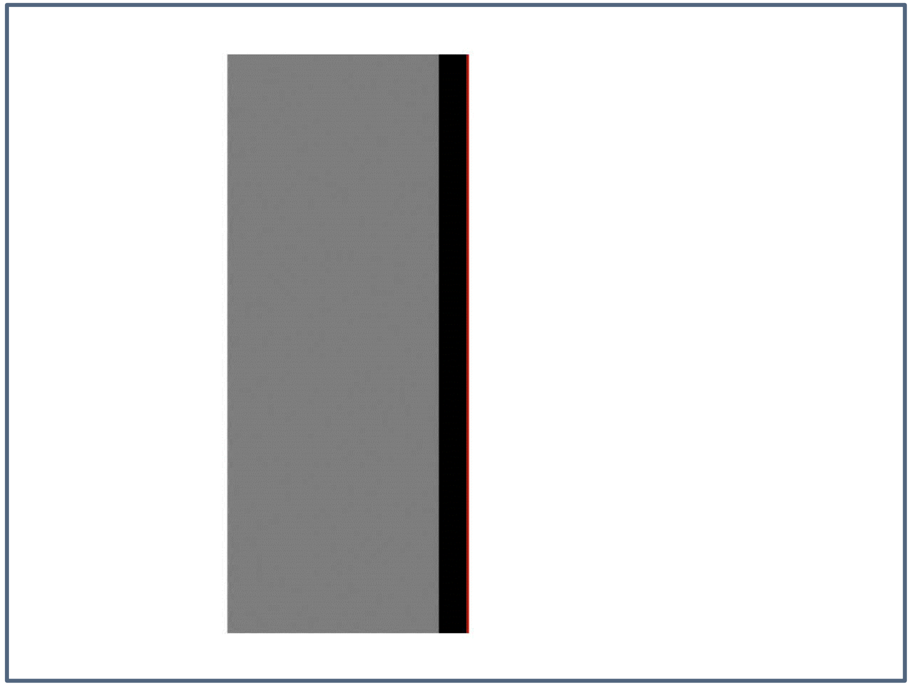
Talks by **Davide Orecchia** and **Alessandro Maffini**

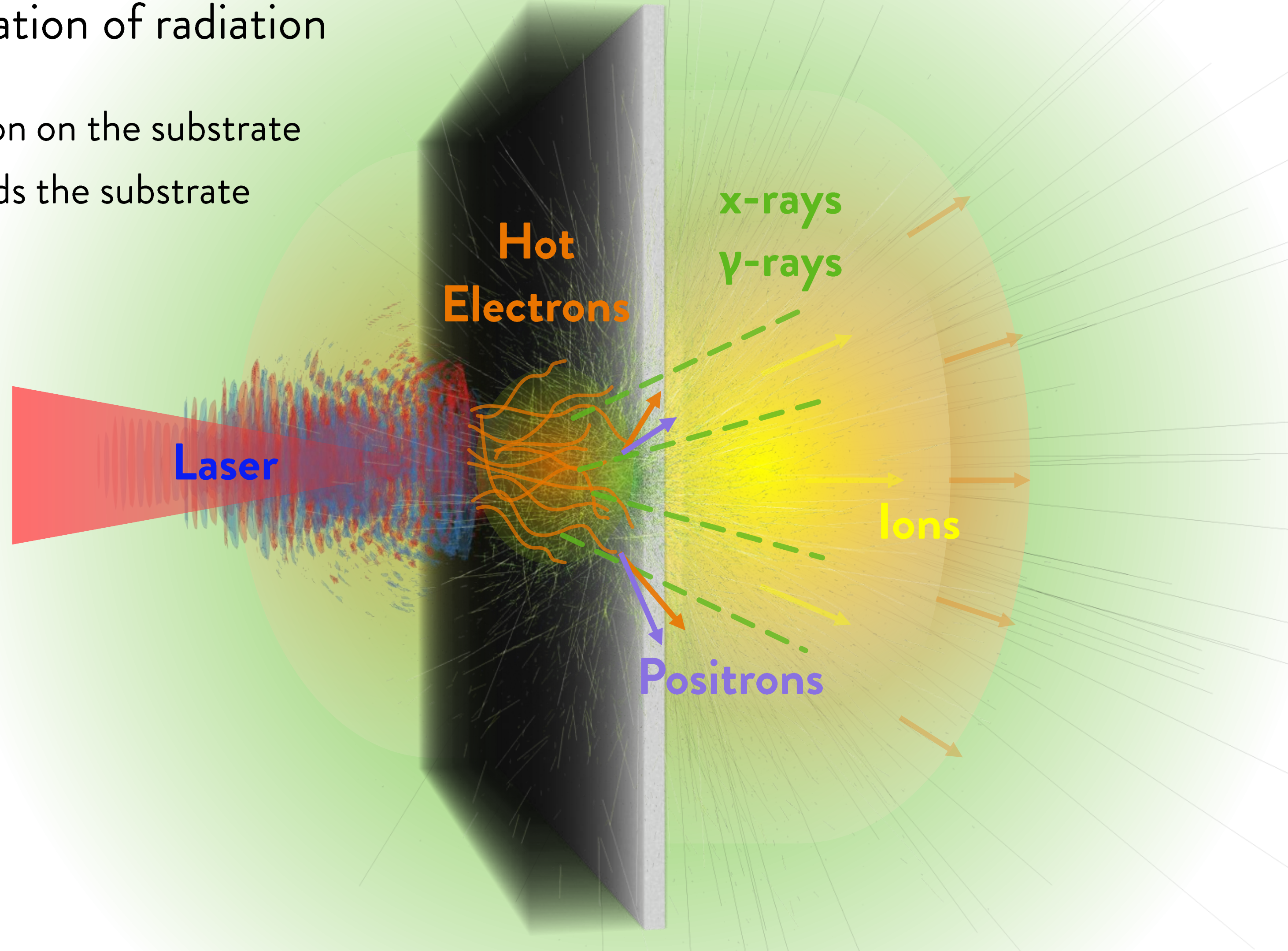
Maffini, A., Orecchia, D., Pazzaglia, A., Zavelani-Rossi, M., & Passoni, M. (2022). Pulsed laser deposition of carbon nanofoam. Appl. Surf. Sci., 599, 153859.

# Laser-Plasma Interaction with Double-Layer Targets (DLTs)

Interesting for Enhanced Acceleration/Generation of radiation

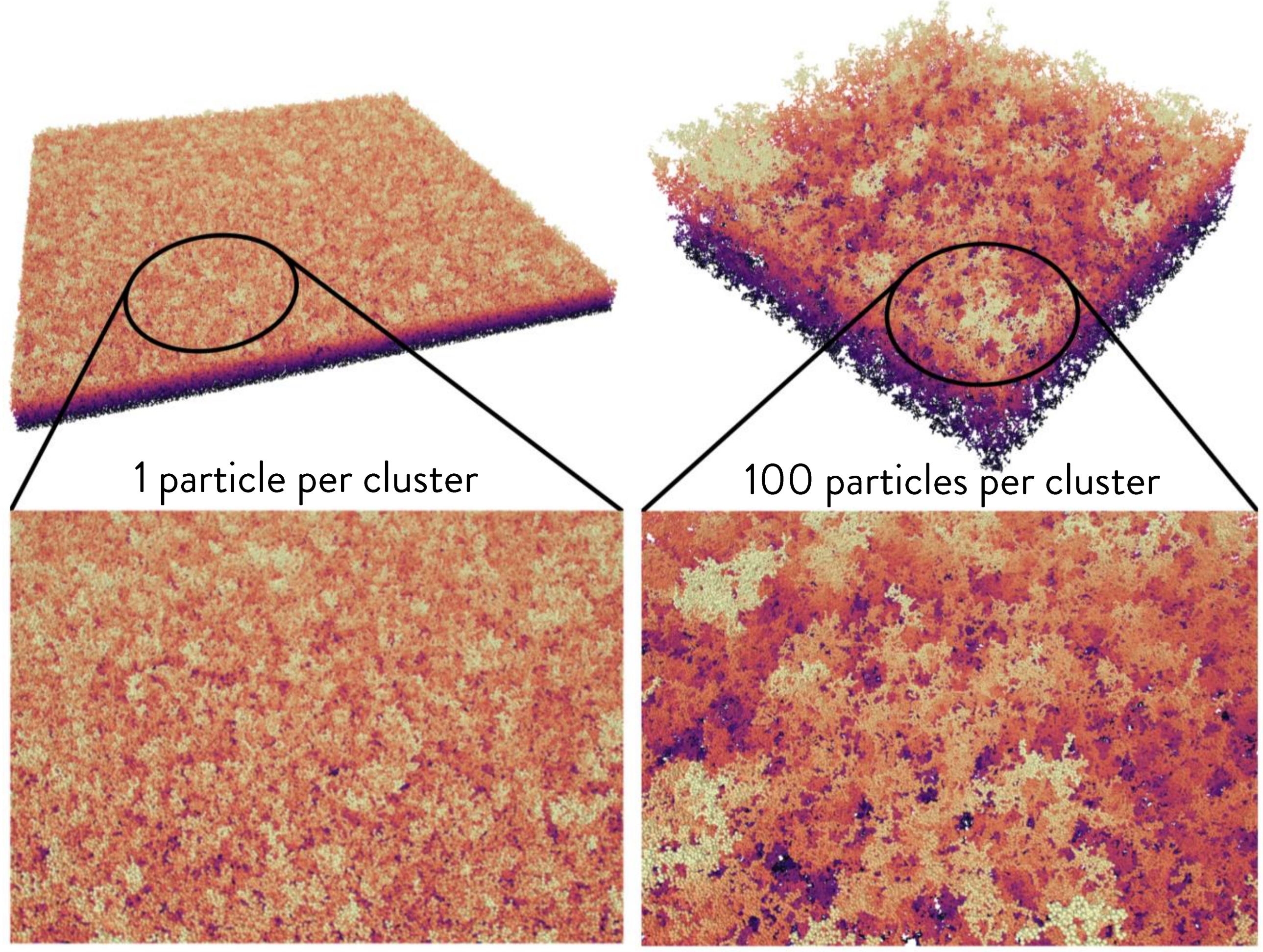
- **Laser** self-focusing inside the foam and laser reflection on the substrate
- Direct Laser Acceleration (DLA) of **Electrons** towards the substrate
- Enhanced TNSA of **Protons** on the rear side



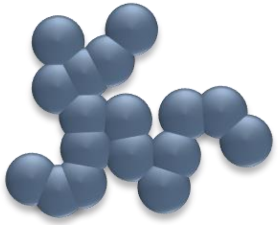


# Modelization of Nanostructured Foams

Modeling of **fractal foam** via the **Diffusion Limited Cluster-Cluster Aggregation** (DLCCA)




Nanoparticles are aggregated to form clusters that diffuse and stick to each other



- Foam thickness increases linearly with the number of deposited clusters
- Foam mean density $\rho$ determined by the number N of nanoparticles per cluster and by the nanoparticle density $\rho_{np}$

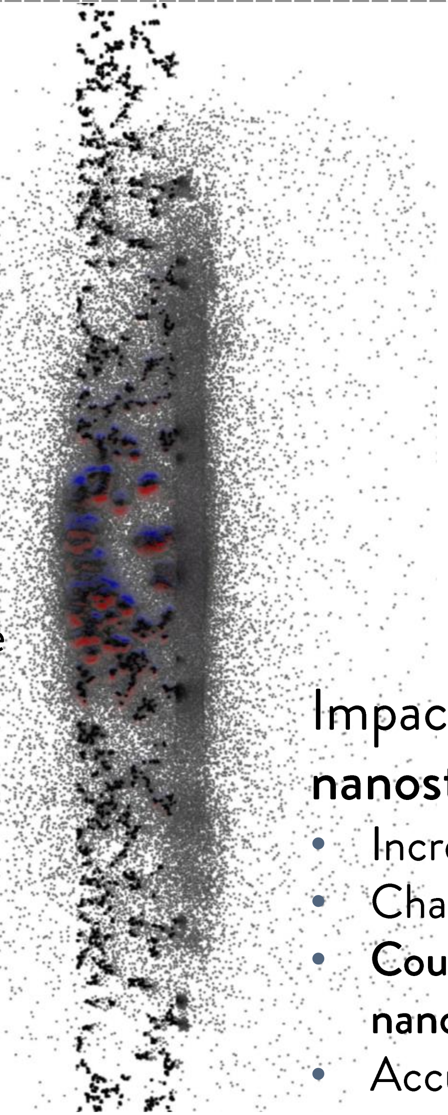
$$\rho = k\rho_{np}N^{-0.556}$$

For our DLCCA growth model → k=0.497

Ambrogioni, K. Numerical modelling of laser-driven proton acceleration with nanostructured targets and TW-class lasers. (2023) M.Sc. Thesis

# Nanostructure and Ionization in DLTs

PIC simulation campaign exploring additional physics with TW and sub-TW lasers



**Bz Field** and electron density in foam with nanostructure during the interaction

**2D/3D Simulations with DLTs**

Laser Intensity = 0.7-4-200x$10^{18}$ W/cm$^2$
$a_0$ = 0.6-1.4-10 λ=0.8
Waist=3-2.5-2.4 μm FWHM=10-40-30 fs
Aluminium Layer Density = 450/80 $n_c$
Aluminium Layer Thickness = 0.2-0.6-1-2 μm
Carbon Foam Density = 0.2-0.3-0.95-2.6-3 $n_c$
Foam Thickness = 0-1.7-1.8-2-3-3.2-4-5.6-6.1-8 μm

With Smilei) and WarpX

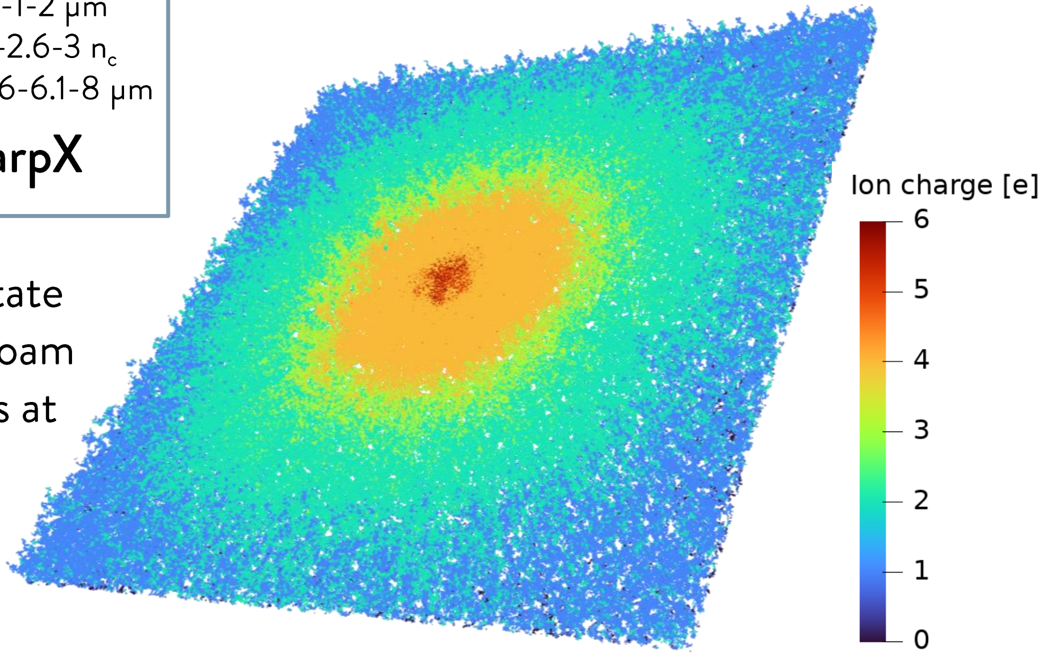
## Impact of **field ionization**

- Almost totally ionised foam and substrate at $a_0$ = 10 but more complex ionization state at $a_0 \sim 1$.
- Increases laser absorption.

## Impact of **foam nanostructure**

- Increases laser absorption.
- Chaotic motion of electrons.
- **Coulomb explosion of nanoparticles.**
- Accurate in 3D geometry.

Ionization state of Carbon foam after 200 fs at $a_0$ = 1.4



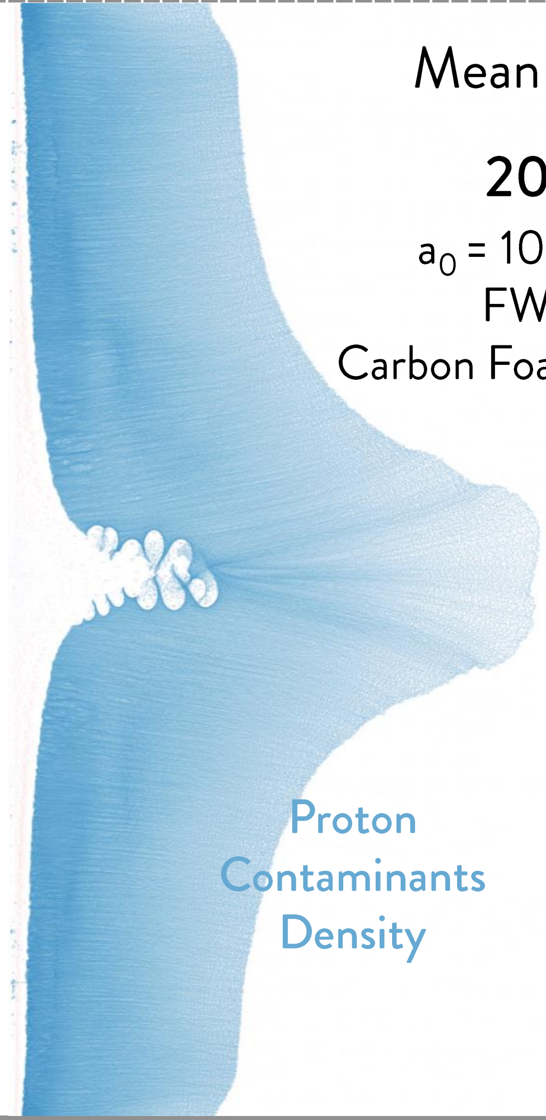
# Ion Acceleration in DLTs

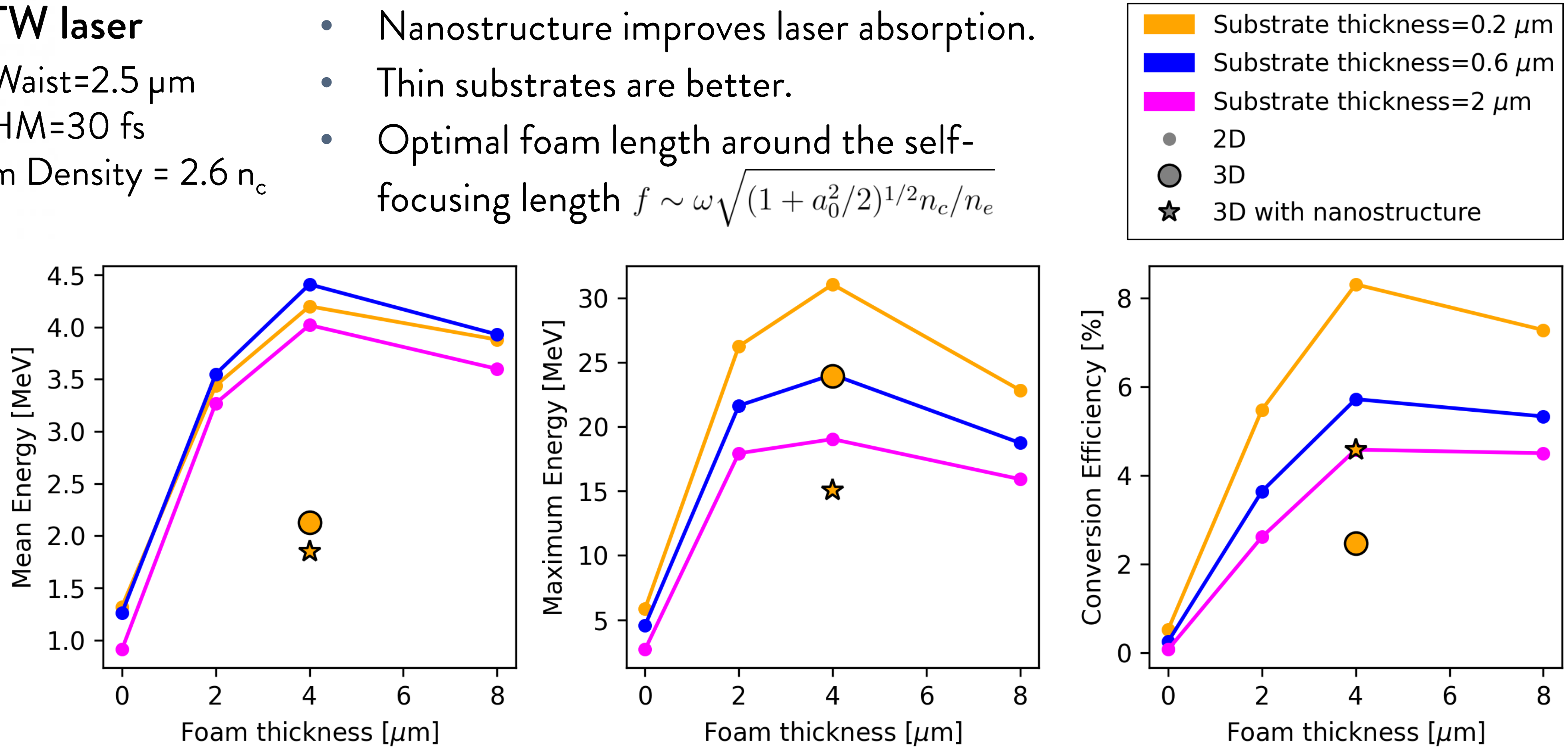
Mean Energy, maximum energy, and conversion efficiency for TNSA protons

**20TW laser**

$a_0$ = 10 Waist=2.5 μm
FWHM=30 fs
Carbon Foam Density = 2.6 $n_c$

- Nanostructure improves laser absorption.
- Thin substrates are better.
- Optimal foam length around the self-focusing length $f \sim \omega\sqrt{(1+a_0^2/2)^{1/2} n_c/n_e}$



# High-Energy Photon Emission in DLTs

Enhanced Acceleration of Electrons in Foam + Dense Substrate

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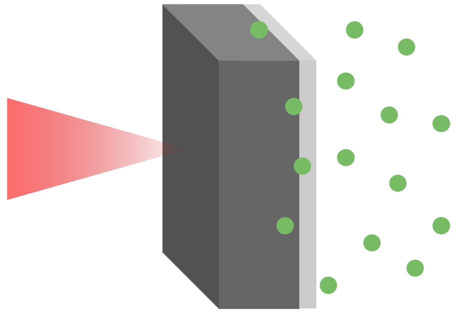
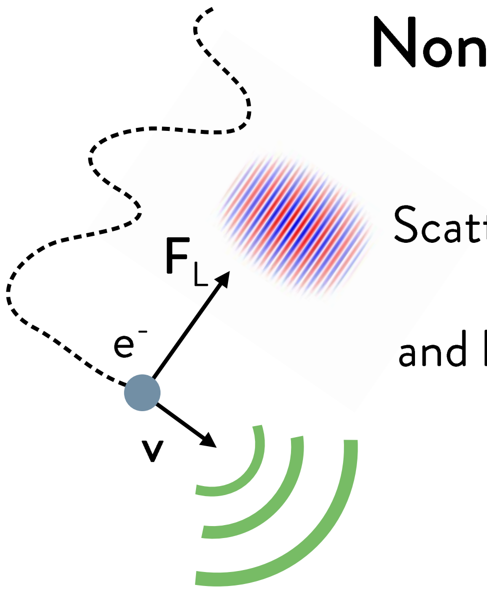
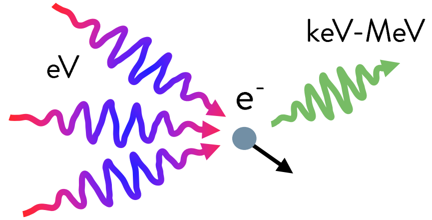
Emission of **High-Energy Photons** (keV-MeV) by Free Electrons



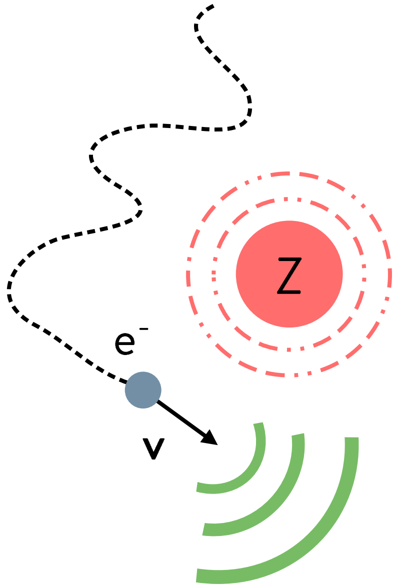



## Non-linear Inverse Compton Scattering (NICS)

Scattering in the electromagnetic fields (synchrotron-like emission) and head-on collision with the reflected laser pulse




Non-linear! $a_0 = \frac{eE_0}{m_e \omega c} \gg 1$



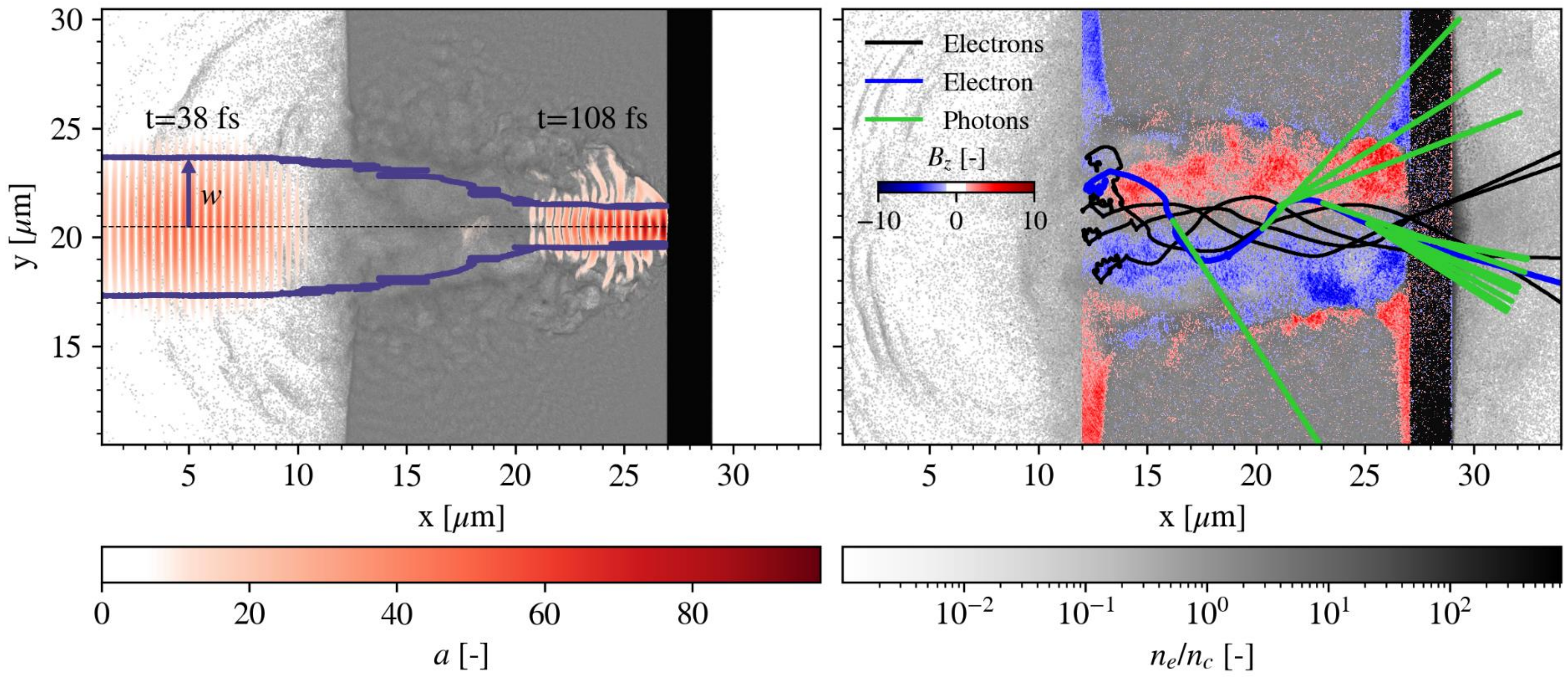

## Bremsstrahlung

Scattering in the Coulomb field of nuclei inside the target
Improved by mm-thick high-Z substrate!

# Non-linear Inverse Compton Scattering (NICS) in DLTs

## Where and when emission occurs: normalized fields and electron density maps + particle trajectories

Laser Intensity = 5.40x1021 W/cm2  Foam Density =  2 nc  Foam  Thickness = 15 μm




Galbiati, M., Formenti, A., Grech, M., & Passoni, M. (2023). Numerical investigation of non-linear inverse Compton scattering in double-layer targets. Front. Phys., 11:1117543.

### 2D Simulations with DLTs

Laser Intensity = 0.9-3.5-5.4-7.8x10$^{21}$ W/cm$^2$
$a_0$ = 20-40-50-60
Aluminium Layer Density = 450 $n_c$
Aluminium Layer Thickness = 2 μm
Carbon Foam Density = 1-2-5-10 $n_c$
Foam Thickness = 5-10-15-20-25 μm

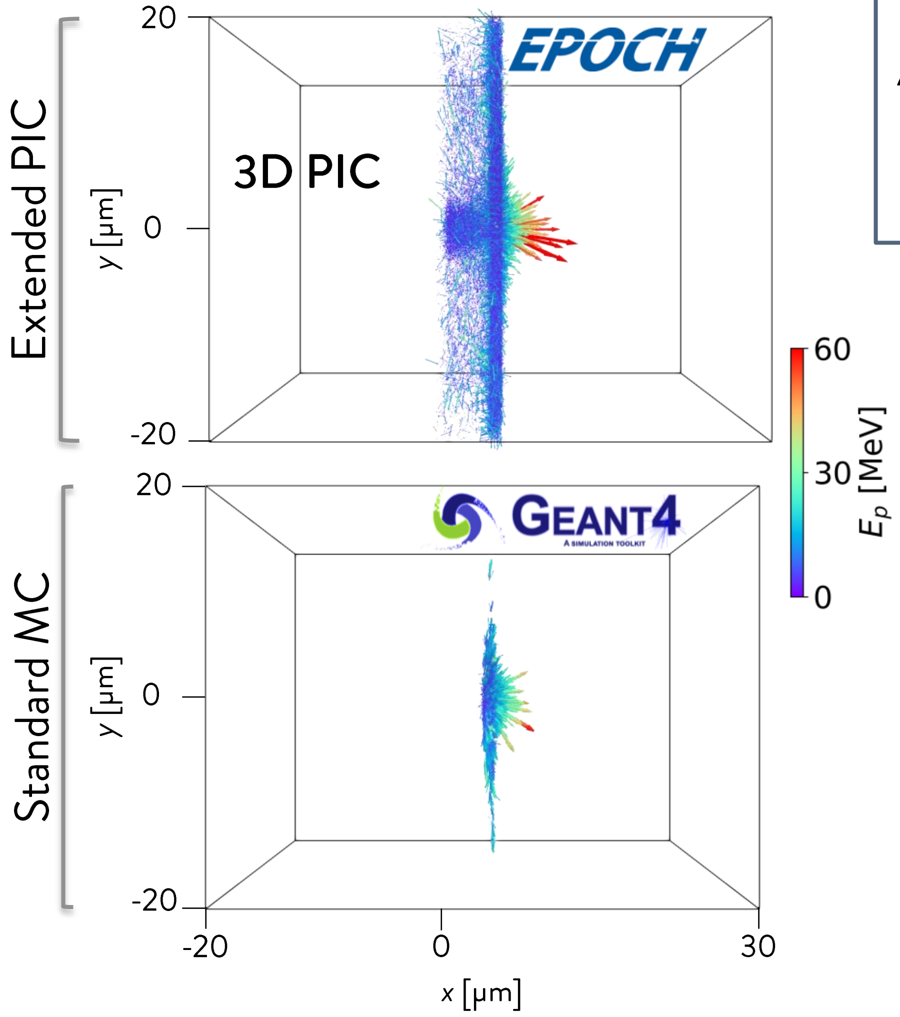
With Smilei

- DLT structure crucial for NICS.
- Long low-density foams enhance emission efficiency and the average energy of emitted photons.
  - Optimal length:

$$f \sim \omega\sqrt{(1+a_0^2/2)^{1/2} n_c/n_e}$$

# Bremsstrahlung in DLTs

Emitted Photons as Arrows

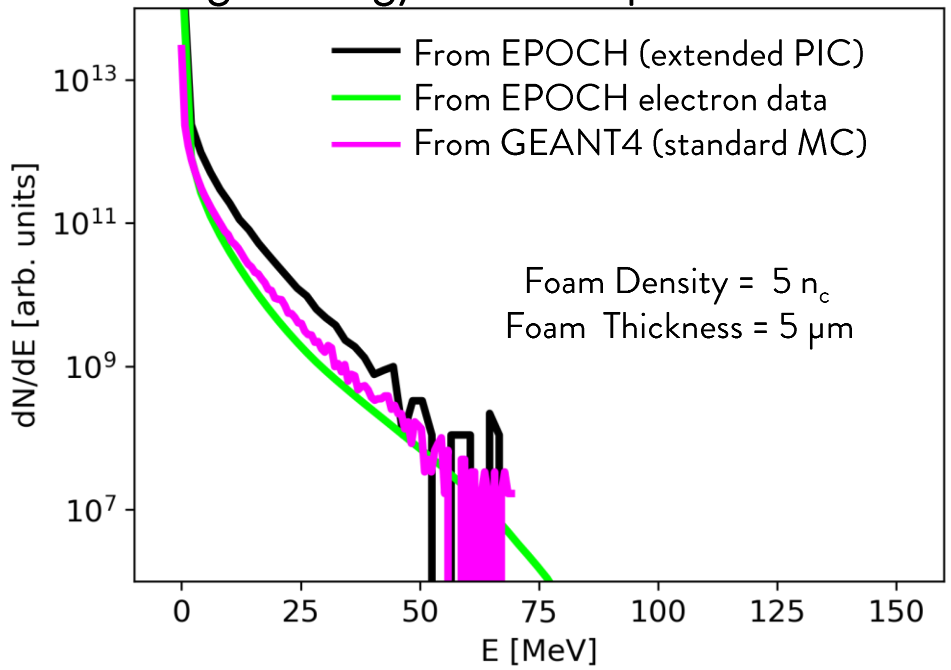



**2D/3D Simulations with DLTs**

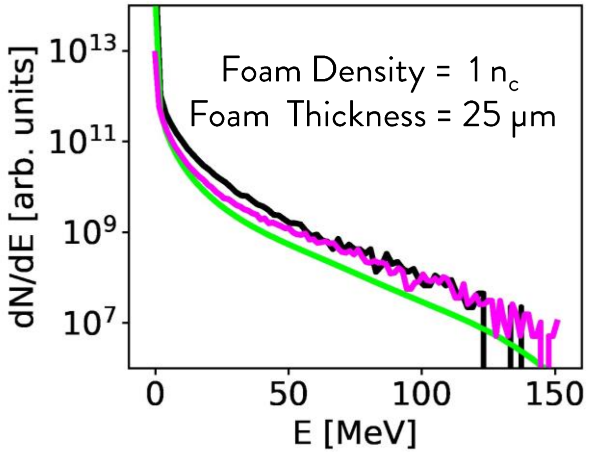
Laser Intensity = $8.65 \times 10^{20}$ W/cm$^2$, $a_0$=20
Aluminium Layer Density = 2D 450 $n_c$ - 3D 80 $n_c$
Aluminium Layer Thickness = 1 μm
Carbon Foam Density = 1-2-5-10 $n_c$
Foam Thickness = 2-5-10-15-20-25 μm

- Affected by recirculation.
- Exponential spectrum.
- Agreement among extended PIC, standard MC, and analytical predictions.
- DLT parameters influence slope and cut-off of emission.

High-energy Photon Spectrum




Formenti, A., Galbiati, M., & Passoni, M. (2022). Modeling and simulations of ultra-intense laser-driven bremsstrahlung with double-layer targets. Plasma Phys. Control. Fusion, 64(4), 044009.

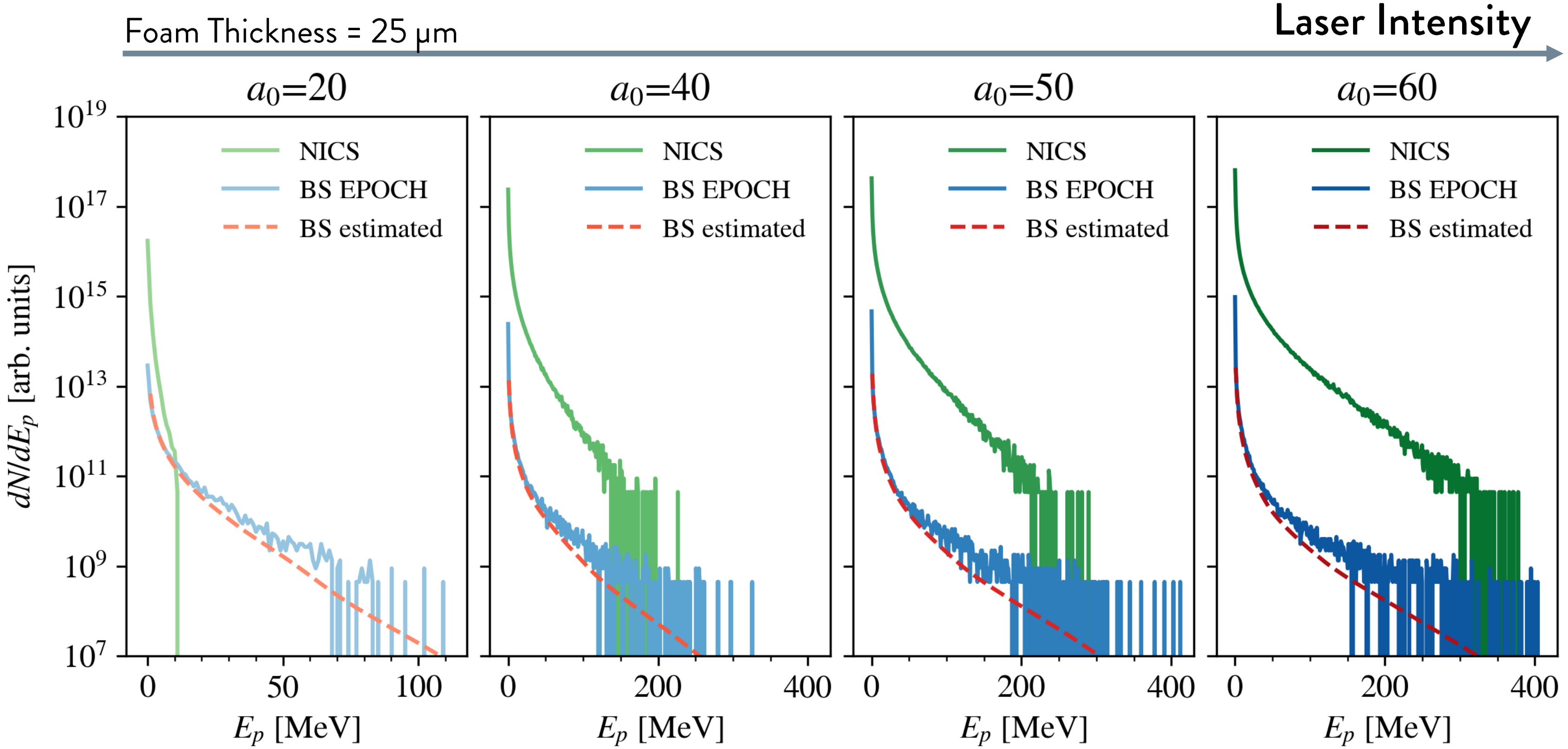


# Bremsstrahlung and NICS

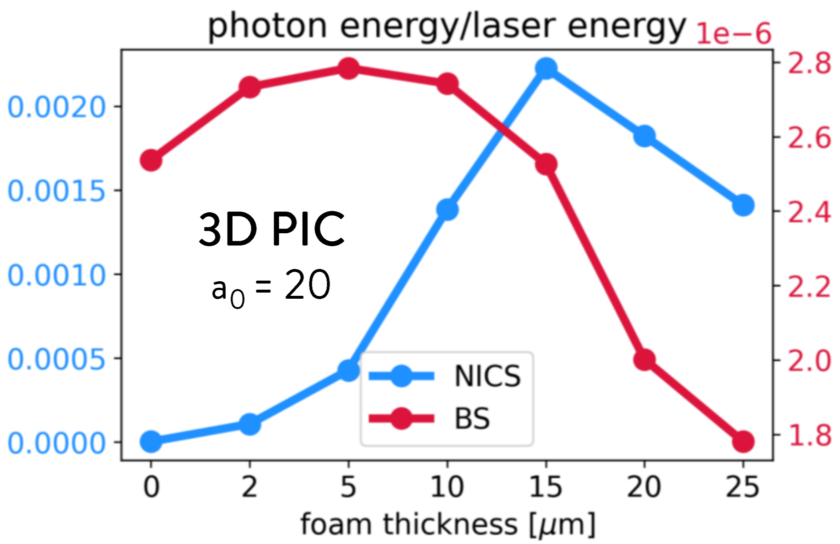
## Conversion efficiencies and spectra for photons

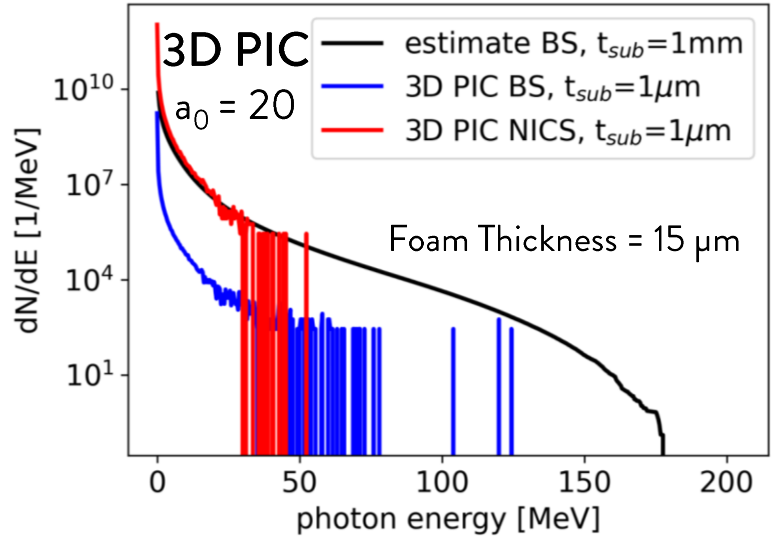
Carbon Foam Density = 1 $n_c$

- Laser intensity and substrate/foam thickness impact the competition




Formenti, A., Galbiati, M., & Passoni, M. Three-dimensional particle-in-cell simulations of laser-driven multi-radiation sources based on double-layer targets. In preparation.



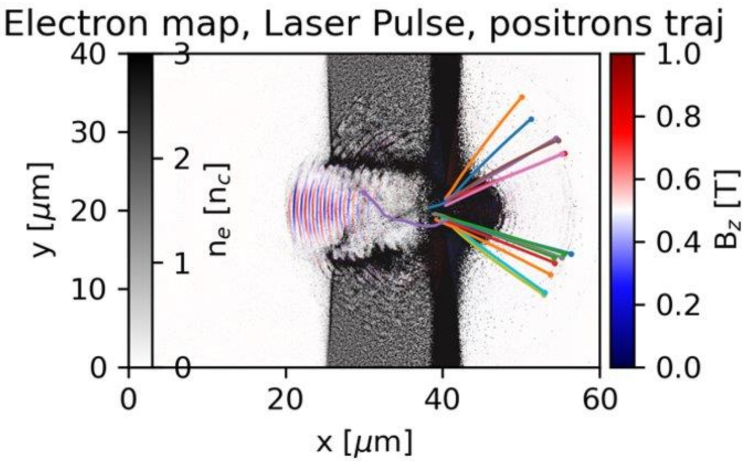



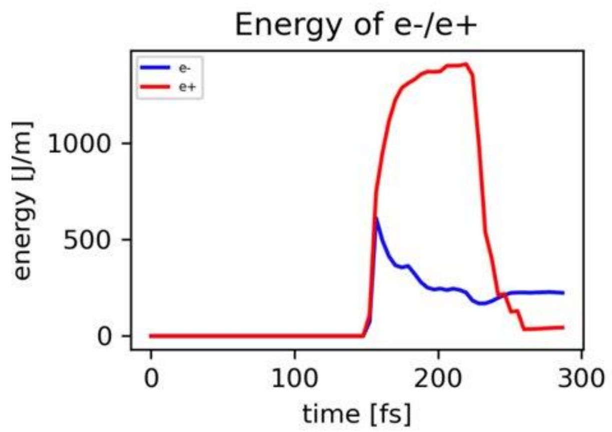
# Positrons, Neutrons, Radioisotopes, …

## Non-linear Breit-Wheeler Pair Production

- Photon decays into pairs while propagating through a strong electromagnetic field
- Positrons are accelerated by TNSA fields
  - $a_0 = 150$ $I = 4.87 \times 10^{22}$ W/cm$^2$

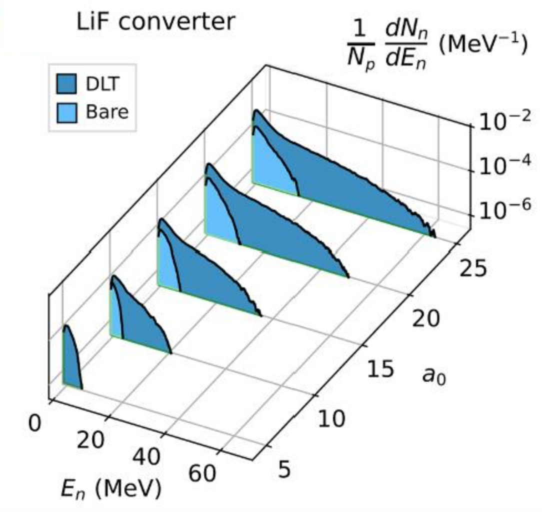
Monaco, L. F. C. (2023) Ongoing M.Sc. Thesis activity.



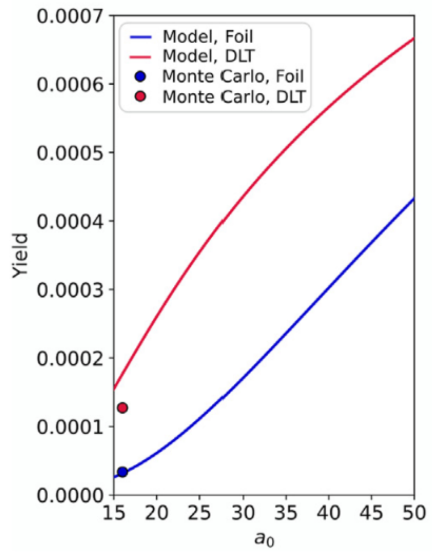

## Enhanced neutron generation in converters from DLT protons

Mirani, F., Maffini, A., & Passoni, M. (2023). Laser-Driven Neutron Generation with Near-Critical Targets and Application to Materials Characterization. Phys. Rev. Appl., 19(4), 044020.




## Cu-64 generation in Ni-64 converter from DLT protons

Maffini, A., Mirani, F., Giovannelli, A. C., Formenti, A., & Passoni, M. (2023). Laser-driven production with advanced targets of Copper-64 for medical applications. Front. Phys, 11:1223023.



# Conclusions

**Numerical investigations** are fundamental to capture the **relevant process in laser-plasma interaction** with advanced near-critical nanostructured targets

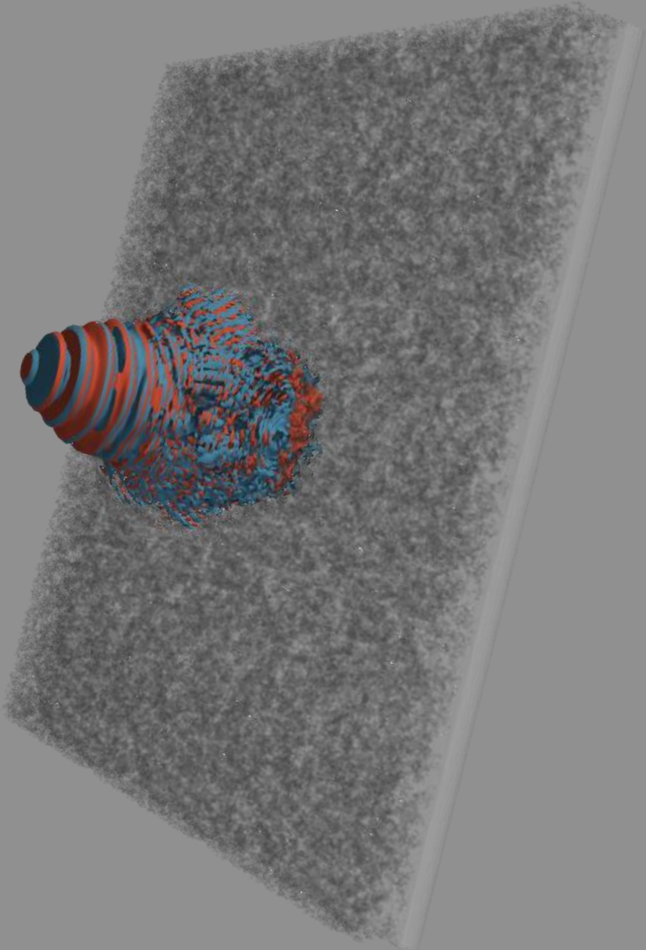
- Double-layer targets **effectively increase laser absorption** and improve particle acceleration/generation
- DLTs can be **optimized** for proton acceleration and photon emission changing target parameters.

**Perspectives**

- Continue the challenging investigation of compact lasers
- Improve simulation tools to perform more accurate simulations
- Experimental campaigns and applications.

**Ion Acceleration on Vega3** $a_0 = 9.37$

**High-Energy Photons on Apollon** $a_0 = 60$



Mini-colloquium: Italian Plasma Physics

**Thank you for your attention!**

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.