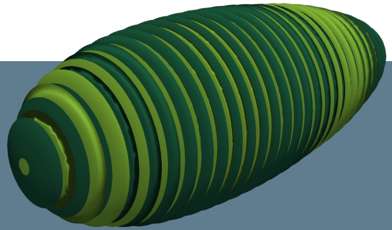
Smilei)

4th Smilei user & training workshop

8-10 November 2023, ELI Beamlines

Numerical Investigation of Laser-Driven Radiation Sources with Double-Layer Targets (DLTs) using Particle in-Cell (PIC) codes

K. Ambrogioni, M. Galbiati, A. Maffini, F. Mirani, L. F. C. Monaco & M. Passoni



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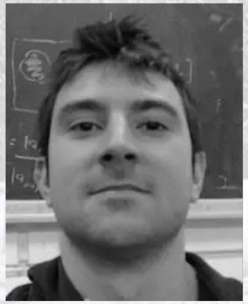
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L. F. C. Monaco

Outline

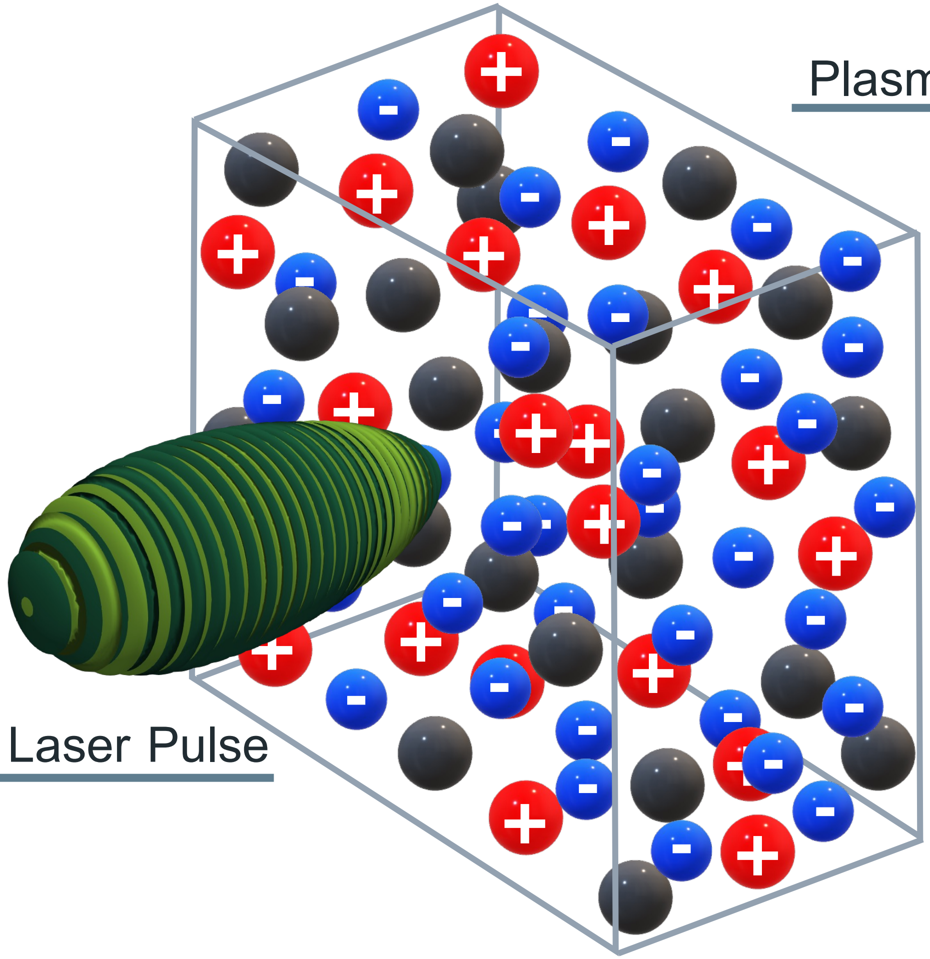
- Radiation Generation via Ultra-Intense Laser-Plasma Interaction
- Use of Smilei for Modelling Advanced Configurations
- Enhanced Proton Acceleration from Tens of TW Lasers with DLTs
- Proton Acceleration from sub-TW Lasers with DLTs
- Pair-Production via Non-Linear Breit-Wheeler in DLTs
- Conclusions and Perspectives

Introduction to Ultra-Intense Laser-Matter Interaction

- Intensity (I) > 10^{18} W/cm^2
- Pulse duration (τ) ~ 10s fs
- Pulse Energy ~ 1 mJ – 10s J
- High Repetition Rate > Hz
- Laser Wavelength ~ 1 μm
- Laser Spot ~ 1 μm

Normalised Vector Potential:

$$a_0 = \frac{e\sqrt{2I}}{m_e \omega c^{\frac{3}{2}}} > 1$$



From target ionisation

Critical electron density:

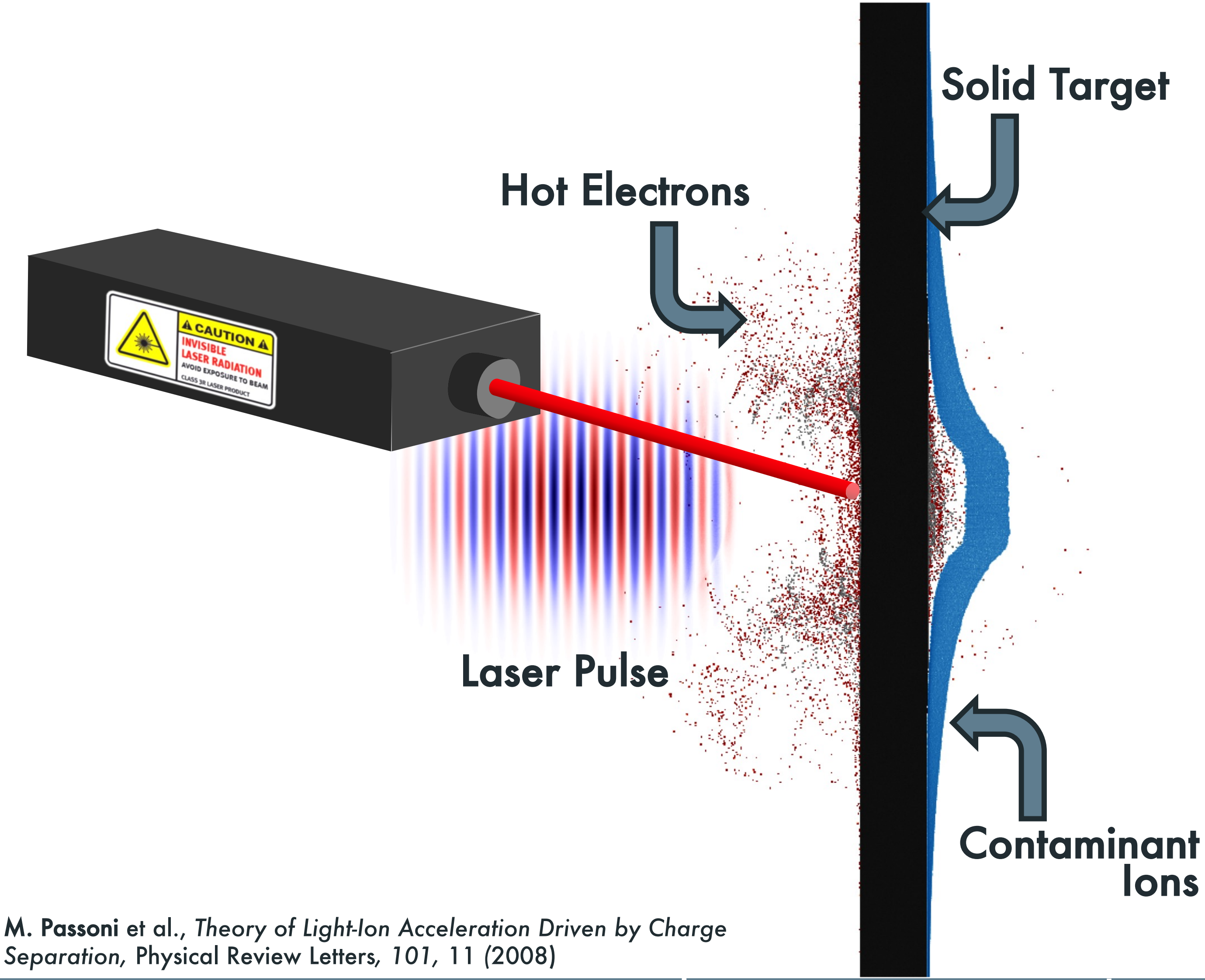
$$n_c = \frac{m_e \omega^2}{4\pi e^2}$$

where n_c of few mg/cm^3

Different interaction regimes:

- Gas: $n_e \ll n_c$
- Near-critical: $n_e \cong n_c$
- Solid: $n_e \gg n_c$

Interaction with Solid Targets: Ion Acceleration



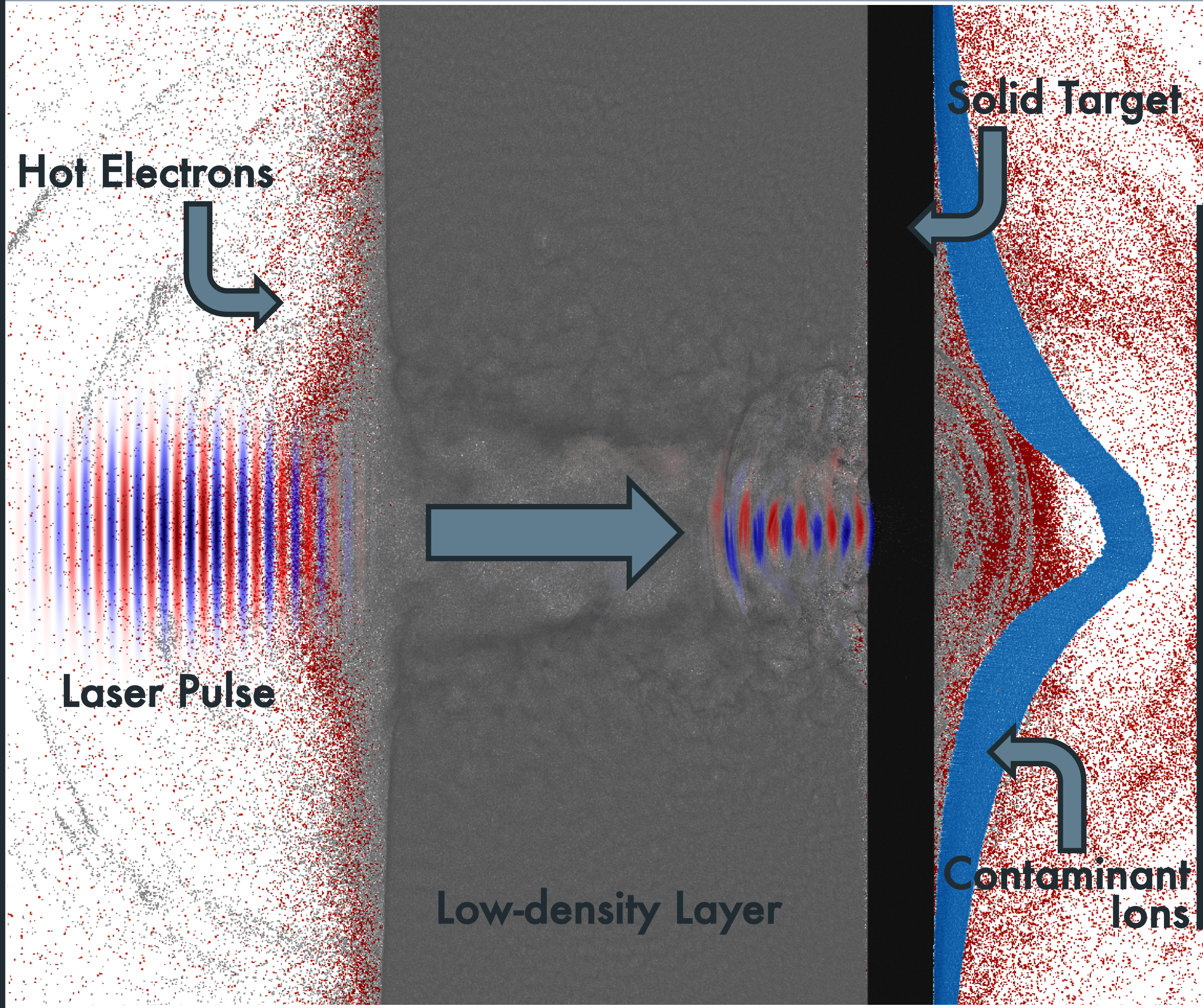
M. **Passoni** et al., *Theory of Light-Ion Acceleration Driven by Charge Separation*, Physical Review Letters, *101*, 11 (2008)

Electron heating and expansion driving
Target Normal Sheath Acceleration (TNSA)

- Effective on low-mass contaminants
- Dependent on the intensity of the laser

- Standard: thin solid targets (~ 1 μm)
- Possible use of **advanced targets** to enhance laser-plasma coupling

Double-Layer Targets: Enhanced TNSA and Secondary Radiation

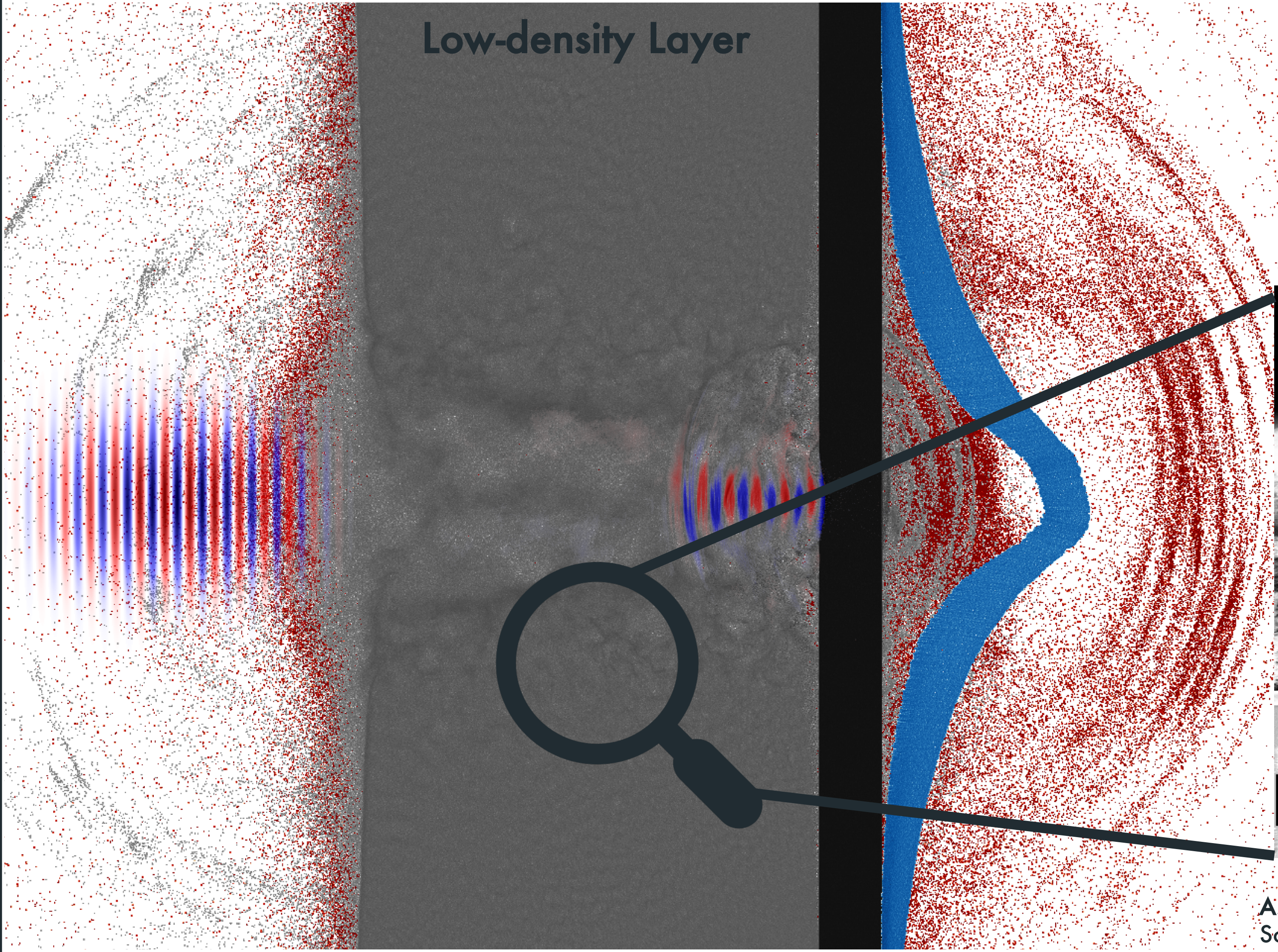


Near-critical layer (~ critical density n_c) on top of the solid foil to create the **Double-Layer Target (DLT)**

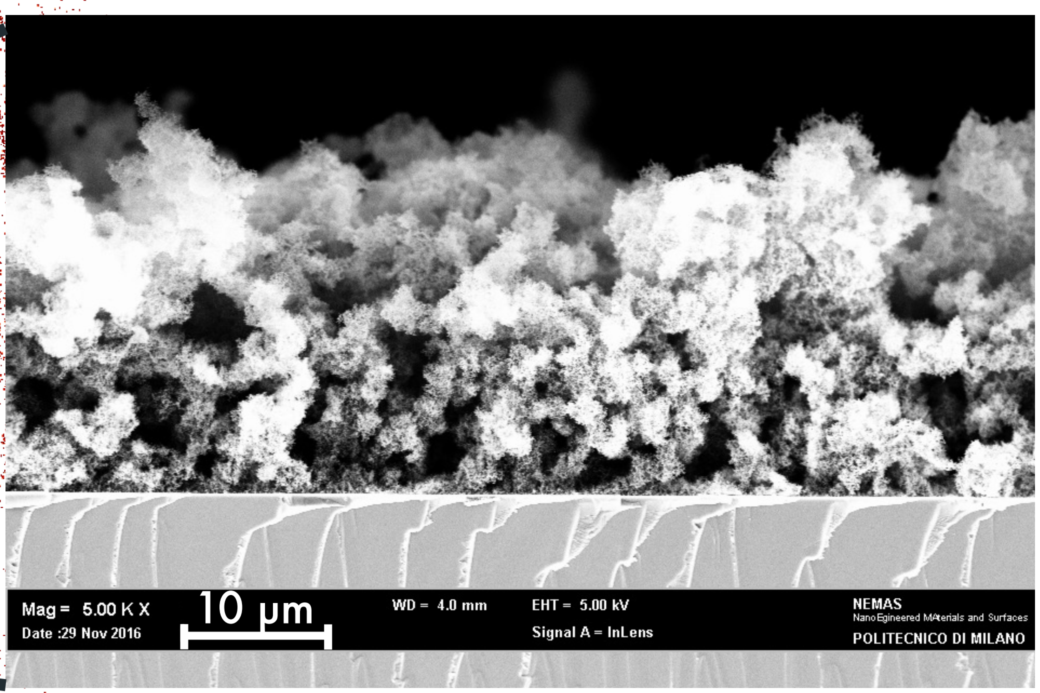
- Enhancement of absorbed laser energy
- Increase of the accelerated ion energy
- **Non-Linear Inverse Compton Scattering (NICS)** in the low-density layer
- Enhanced **Bremsstrahlung** in high-Z solid foils
- **Non-Linear Breit-Wheeler** and **Bethe-Heitler** pair production
- Increased **neutron generation** and **radioisotope production**

I. Prencipe et al., *Efficient laser-driven proton and Bremsstrahlung generation from cluster-assembled foam targets* , New Journal of Physics, 23, 093015 (2021)

Double-Layer Targets: Near-Critical Layer



<u>HOW?</u> @ NanoLab carbon foams deposited on metallic foils via Pulsed Laser Deposition (PLD)



A. Maffini et al., *Pulsed Laser Deposition of Carbon Nanofoam*, Applied Sufrace Science, *599*, 153859 (2022)

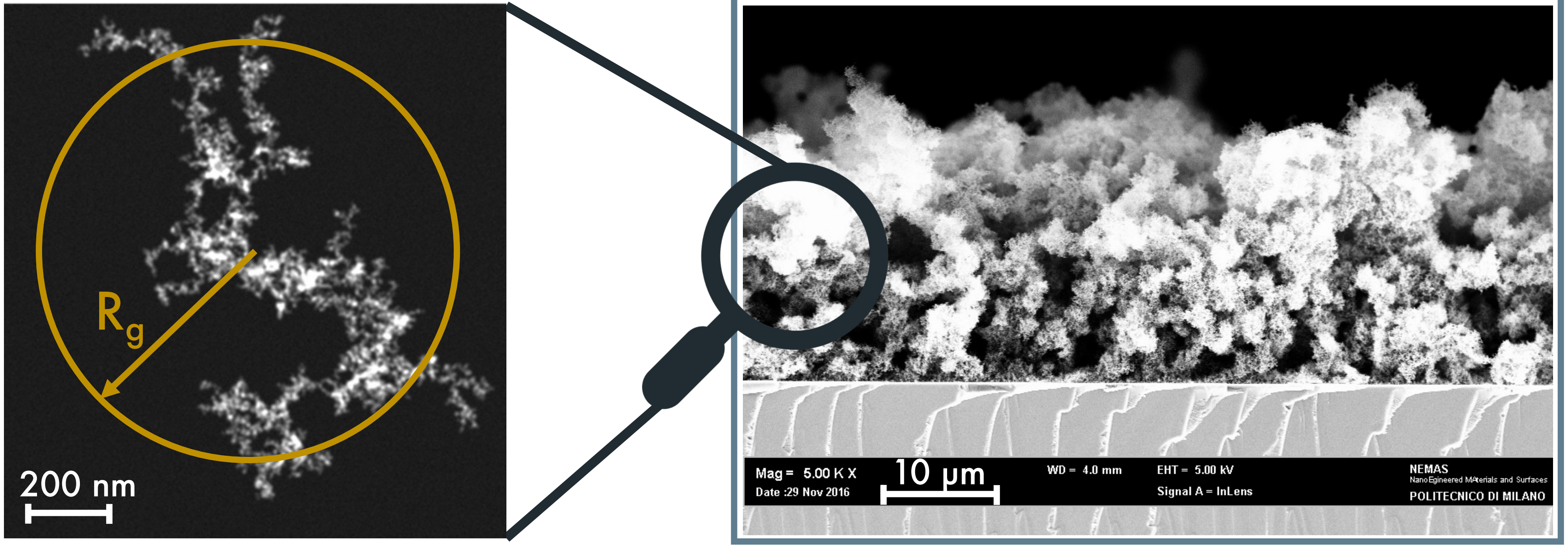
Double-Layer Targets: Near-Critical Layer

Fractal structure composed of **sub-wavelength nanoparticles** (few nm) stick together to form clusters.
Ensemble of clusters generates the foam.

Cluster dimension depends on **deposition method** and defined by **gyration radius** (R_g)

Gyration radius ~ **number of particles per cluster** via **fractal scaling**

Foam density ~ gyration radius of the clusters



A. Maffini et al., *Pulsed Laser Deposition of Carbon Nanofoam*, Applied Sufrace Science, *599*, 153859 (2022)

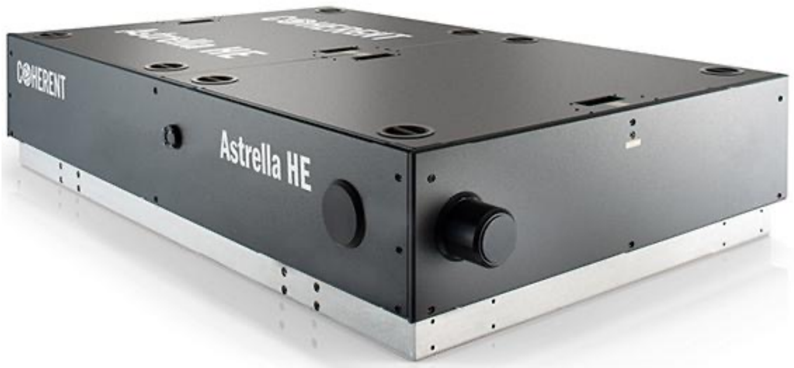
Motivations of the Research

<u>Double-layer targets (DLTs):</u>

- allow efficient laser-driven **acceleration of particles**
- pose bases for **secondary radiation generation** in laser-plasma interaction

Potentially compact and cheap radiation sources

Multiple tuneable radiation fields



Possible use of table-top laser systems (TW or sub-TW class)

Multipurpose sources allowing different radiation fields

Use of Smilei for Simulations of Laser-Driven Radiation Generation

Numerical **Particle-in Cell** tools enable deep understanding of physics and parameter optimisation

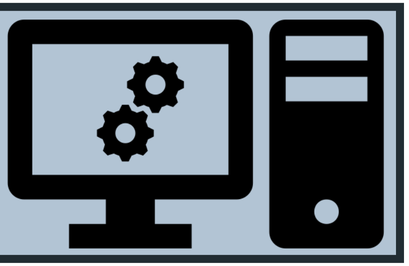
Smilei allows to study additional processes thanks to appropriate Monte Carlo modules:

- Ionisation of the target
- Pair production
- Photon generation

```
Species(…
        ionization_model = 'Tunnel',
        ionization_electrons = 'ele',
        …
        radiation_photon_species = 'photon',
        …
        multiphoton_Breit_Wheeler = ['ele', 'pos'],
        …
)
```

Smilei allows to introduce external input file to simulate the real structure of DLTs

Simulation of foam Structure



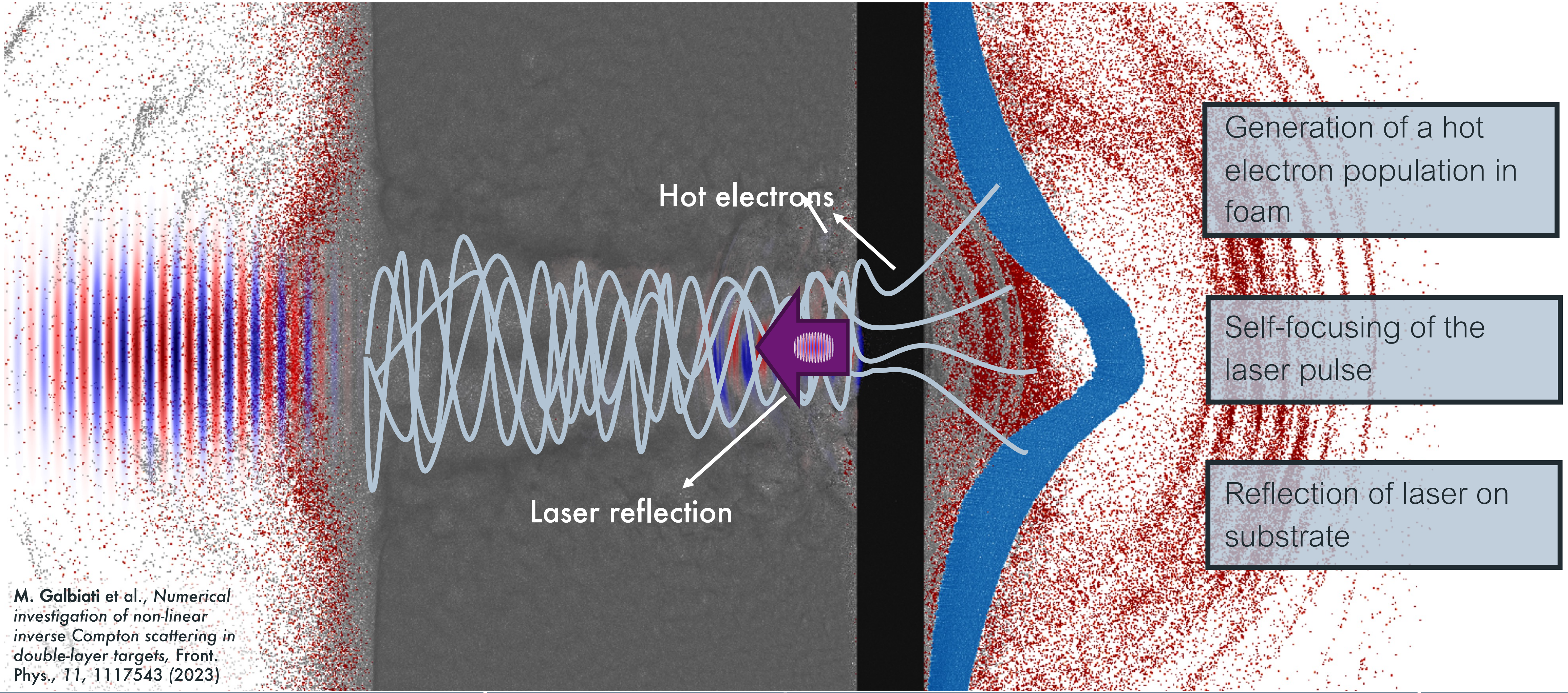
↓

Output to foam.h5 file

↓

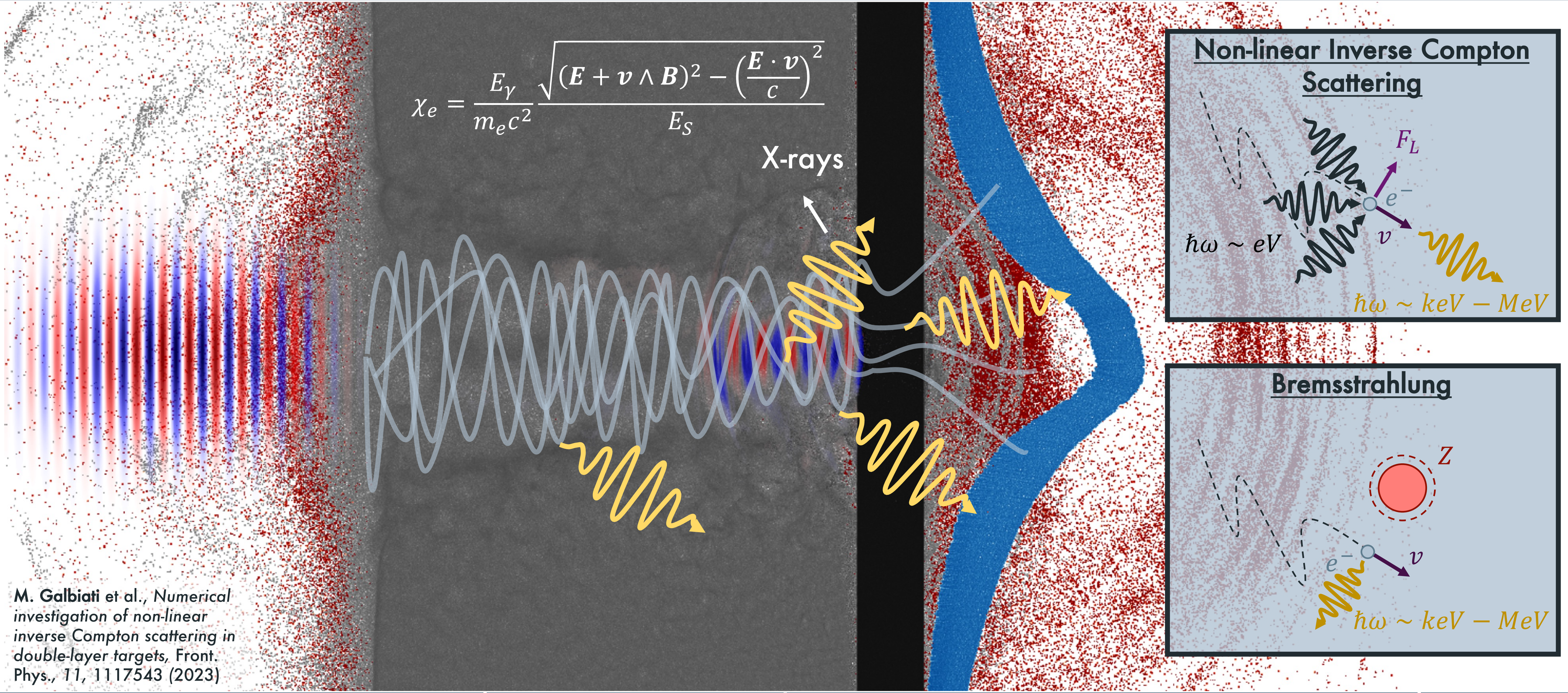
```
Species(…
        position_initialization = 'Random',
        momentum_initialization = 'maxwell-juettner',
        number_density = '/path/to/dataset/foam.h5',
        …
)
```

Double-Layer Targets: Photon and Pair Generation



M. Galbiati et al., *Numerical investigation of non-linear inverse Compton scattering in double-layer targets*, Front. Phys., *11*, 1117543 (2023)

Double-Layer Targets: Photon and Pair Generation



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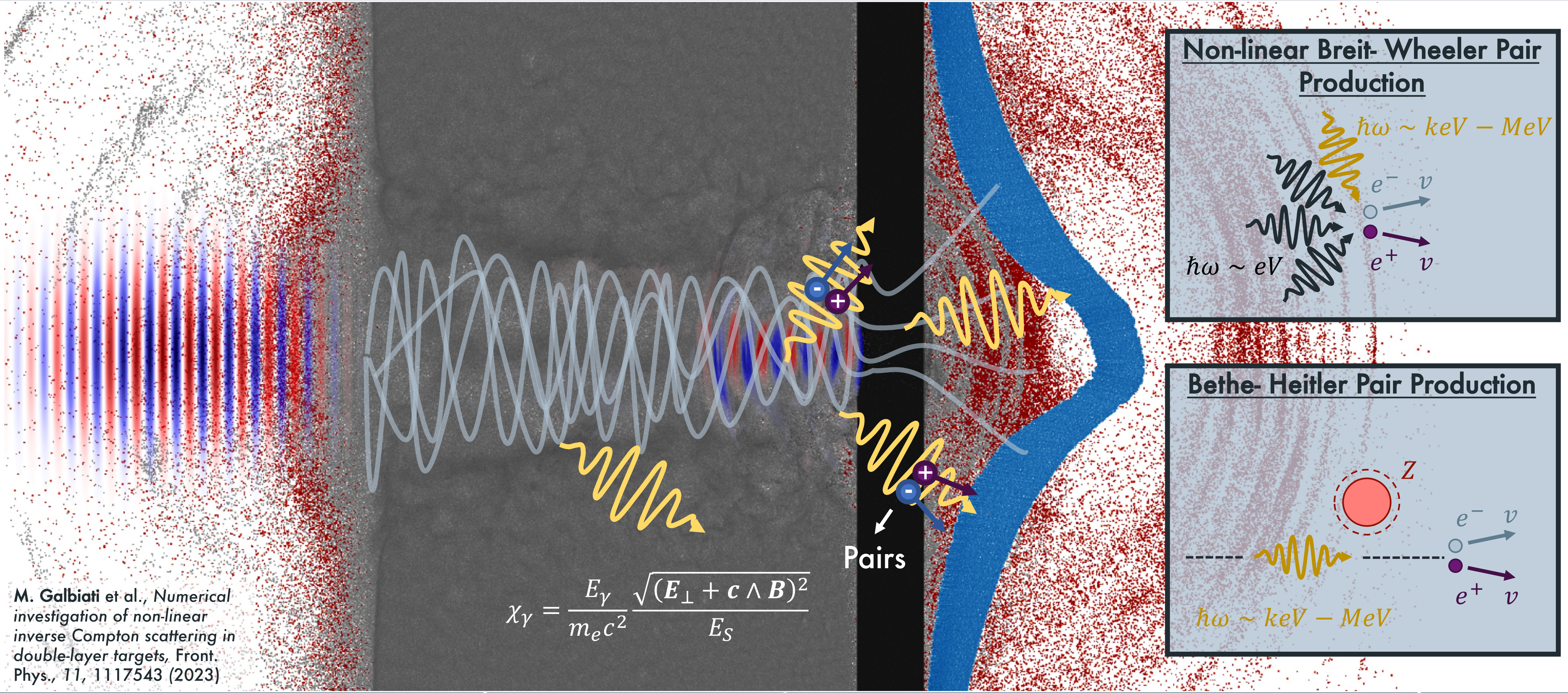
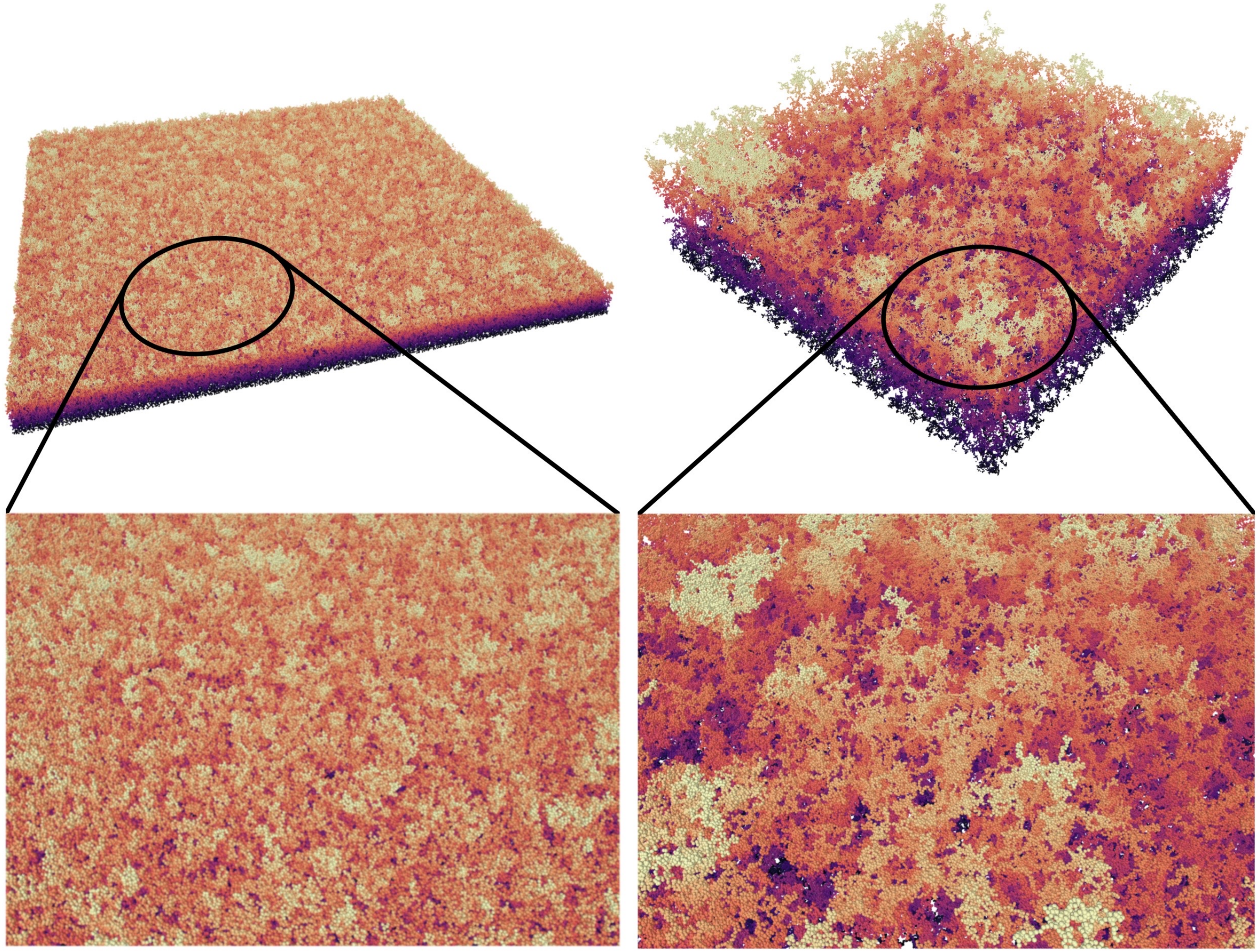
Double-Layer Targets: Photon and Pair Generation



$$\chi_\gamma = \frac{E_\gamma}{m_e c^2} \frac{\sqrt{(\boldsymbol{E}_\perp + \boldsymbol{c} \wedge \boldsymbol{B})^2}}{E_S}$$

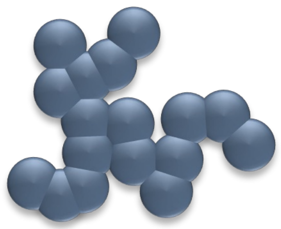
M. Galbiati et al., *Numerical investigation of non-linear inverse Compton scattering in double-layer targets*, Front. Phys., 11, 1117543 (2023)

Modelling of Nanostructured Foams



Modelling 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 **ρ** determined by the **number N of nanoparticles per cluster** and by the **nanoparticle density** $\boldsymbol{\rho_{np}}$

$$\rho = k\rho_{np}N^{-0,556}$$

For our DLCCA model **k=0,497**

Ambrogioni K., *Numerical Modelling of Laser-Driven Proton Acceleration with Nanostructured Targets and TW-Class Lasers*, MSc. Thesis (2023)

Enhanced Proton Acceleration from Tens of TW Lasers with DLTs

3D simulation for the optimal DLT in Smilei) on CINECA - Galileo100 including realistic foam-like structure of the near-critical layer. Foam generated with proprietary code. The target simulated as a completely ionised plasma.

Simulation Parameters	
Box Size [x;y;z] (µm)	[70;50;50]
Points per µm [x;y;z]	[25;25;25]
CFL	0,98
Duration (fs)	225
Processing Units	1536
Boris pusher, Silver-Müller/Absorbing in x, Periodic/Periodic in [y,z], Load Balancing	

Laser Parameters	
a_0	10
Intensity (W/cm²)	$2{,}0 \times 10^{20}$
Laser Spot (µm)	2,4
Wavelength (µm)	0,8
Pulse Duration (fs)	30
Polarisation	Linear (y-plane)
Incidence Angle	0°
Shape in Time	Gaussian
Shape in Space	Gaussian

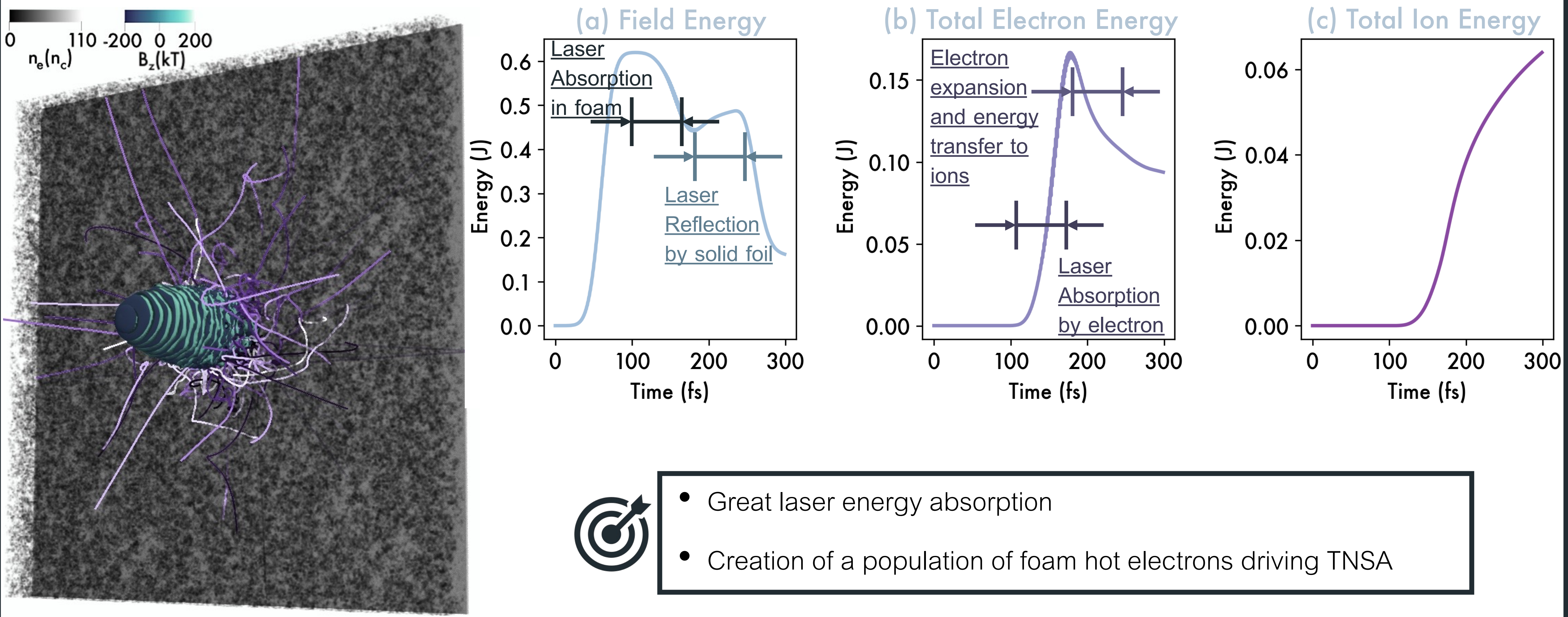
Foam Parameters	
Element	C
Mean Density (n_c) [e;i]	[2,6;0,43]
Nanoparticle Density (n_c) [e;i]	[20,8;3,5]
Particles per Cell [e;i]	[20;2]
Thickness (µm)	4,0
Nanoparticle Radius (nm)	40

Solid Foil Parameters	
Element	Al
Density (n_c) [e;i]	[80;6,2]
Particle per Cell [e;i]	[10;1]
Thickness (µm)	0,2

Contaminant Layer Parameters	
Element	H
Density (n_c) [e;i]	[10;10]
Particle per Cell [e;i]	[100;100]
Thickness (µm)	0,05

Maffini A. et al., *Towards compact laser-driven accelerators: exploring the potential of advanced double-layer targets*, EPJ Tech. Instrum., 10, 15 (2023)

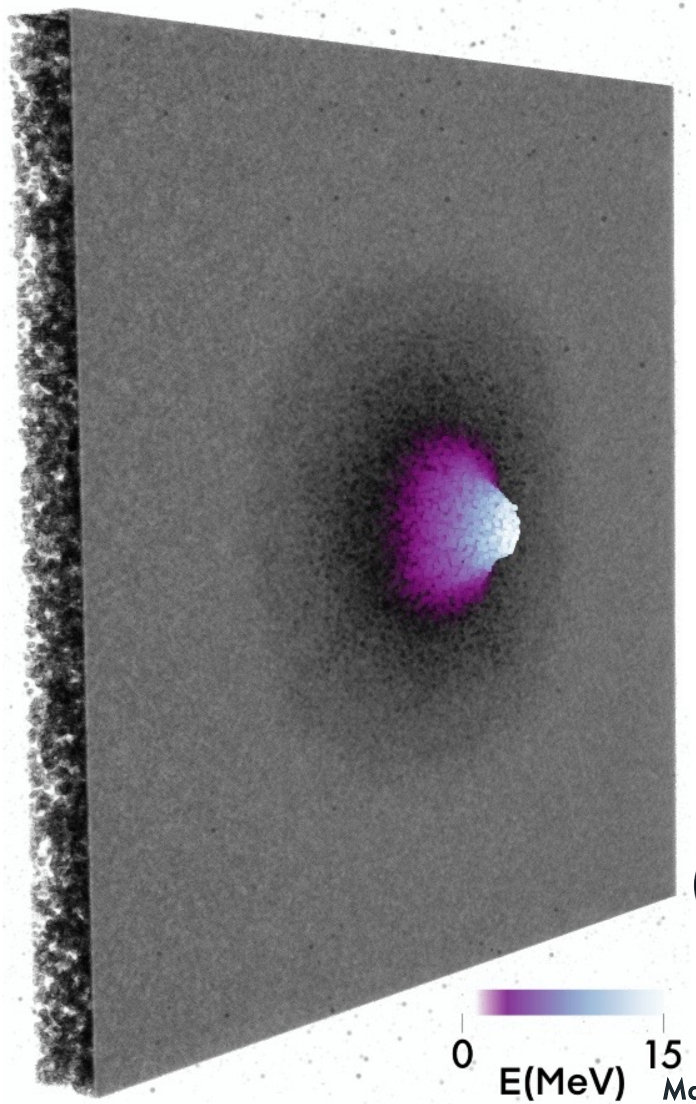
Enhanced Proton Acceleration from Tens of TW Lasers with DLTs

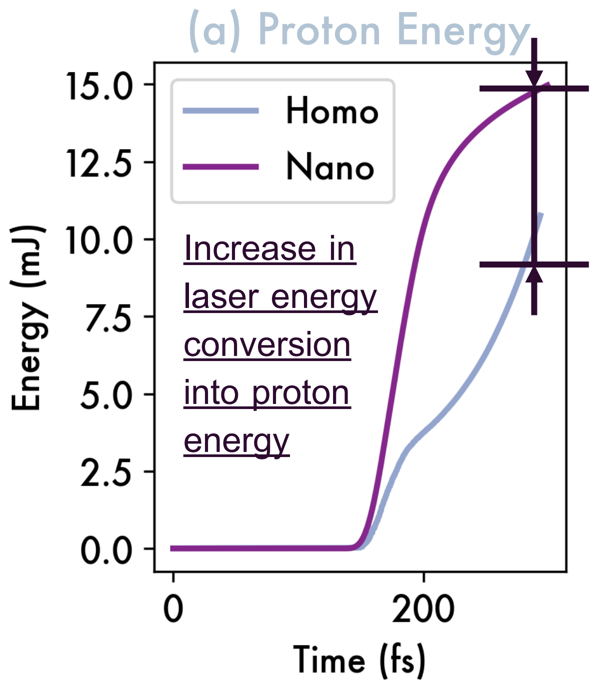


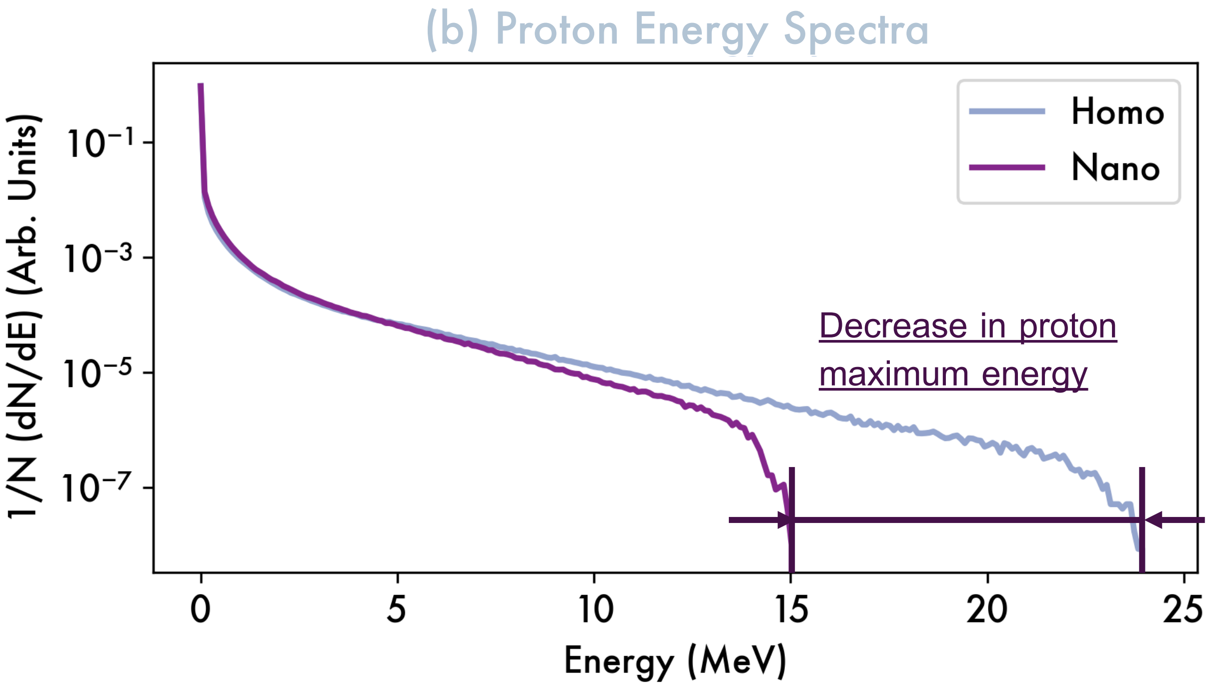
- Great laser energy absorption
- Creation of a population of foam hot electrons driving TNSA

Maffini A. et al., *Towards compact laser-driven accelerators: exploring the potential of advanced double-layer targets*, EPJ Tech. Instrum., 10, 15 (2023)

Proton Acceleration from sub-TW Lasers with DLTs







- Increase in laser conversion efficiency due to Coulomb explosion of nanoparticles in nanostructured foam and reflection reduction
- Decrease in proton maximum energy due to the reduction of resonant effects (e.g., Direct Laser Acceleration (DLA)) due to nanostructure

Maffini A. et al., *Towards compact laser-driven accelerators: exploring the potential of advanced double-layer targets*, EPJ Tech. Instrum., 10, 15 (2023)

Proton Acceleration from sub-TW Lasers with DLTs

2D/3D simulations for the optimal DLT in Smilei on CINECA - Galileo100 including realistic foam-like structure of the near-critical layer. Foam generated with proprietary code for Diffusion-Limited Cluster-Cluster Aggregation (DLCCA).

Simulation Parameters	
Box Size [x;y;z] (μm)	2D [100,56] 3D [70;50;50]
Points per μm [x;y;z]	2D [65,65] 3D [25;25;25]
CFL	0,98
Duration (fs)	2D 500 3D 225
Processing Units	2D 288 3D 1536
Boris pusher, PML/Absorbing in x, Periodic/Periodic in [y,z], Load Balancing	

Laser Parameters	
a_0	1,4
Intensity (W/cm²)	$4,0 \times 10^{18}$
Laser Spot (μm)	3,0
Wavelength (μm)	0,8
Pulse Duration (fs)	10
Polarisation	Linear (y-plane)
Incidence Angle	0°
Shape in Time	Gaussian
Shape in Space	Gaussian

Foam Parameters	
Element	C
Mean Density (n_c) [i]	[0,16]
Nanoparticle Density (n_c) [i] (if nanostructured)	[4,2]
Thickness (μm)	3,0
Nanoparticle Radius (nm) (if nanostructured)	25
Particles per cell [i,e]	2D [~4, ~10] 3D [2, 0]

Solid Foil Parameters	
Element	Al
Density (n_c) [i]	2D [34,6] 3D [6,15]
Thickness (μm)	1,0
Particles per cell [i,e]	2D [~5, ~30] 3D [1, 0]

Contaminant Layer Parameters	
Element	H
Density (n_c) [e,i]	[10,10]
Thickness (μm)	0,05
Particles per cell [i,e]	2D [100, 100] 3D [60, 60]

Ambrogioni K., *Numerical Modelling of Laser-Driven Proton Acceleration with Nanostructured Targets and TW-Class Lasers*, MSc. Thesis (2023)

Proton Acceleration from sub-TW Lasers with DLTs

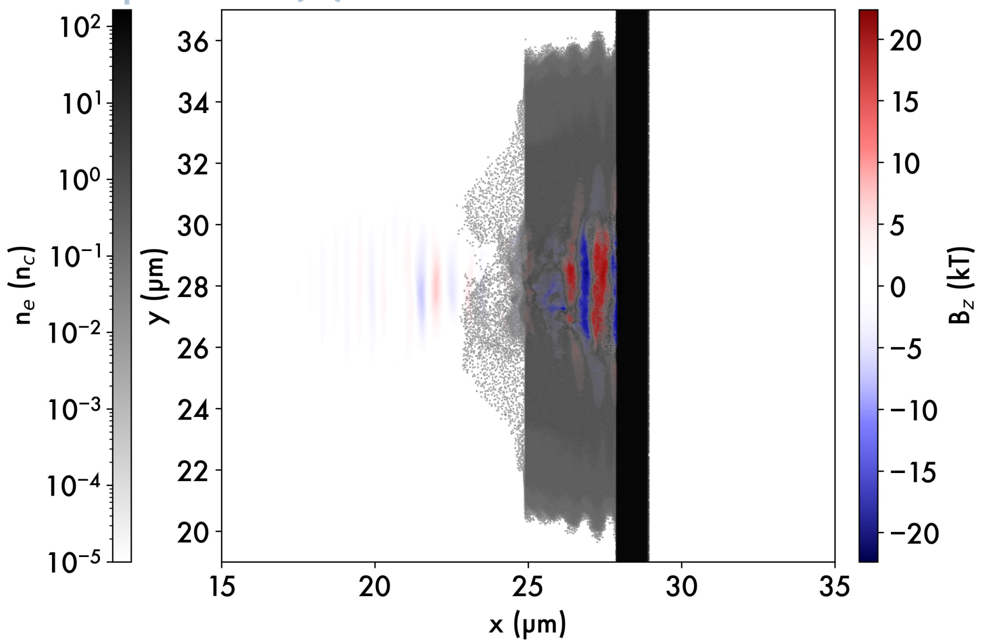
Three 2D simulations to evaluate effects of tunnel ionisation and nanostructure

(a) Homogeneous foam w/ tunnel ionisation: **C**: 0-times ionised, **Al**: 3-times ionised

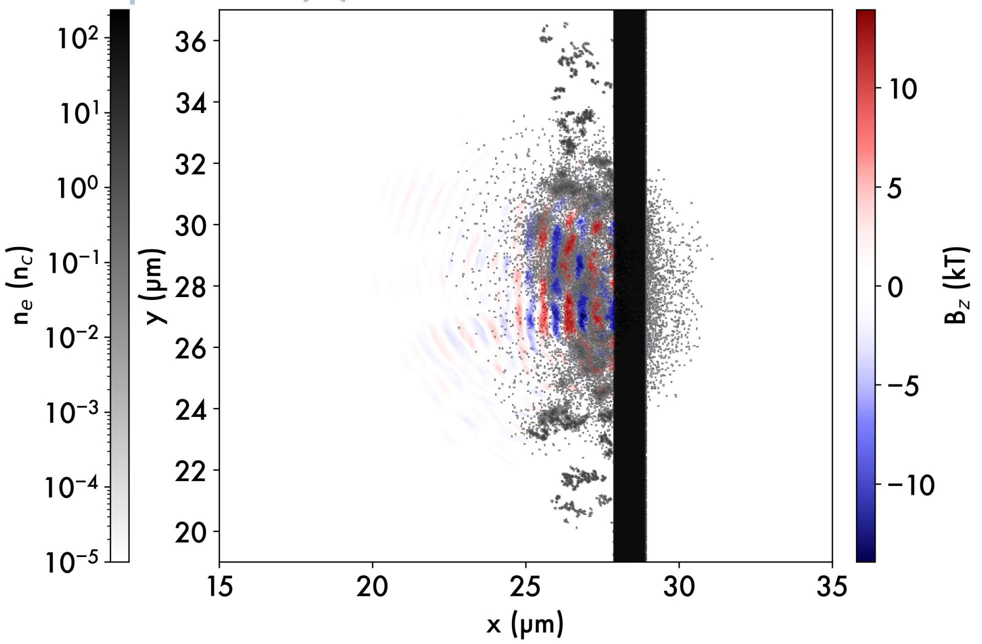
(b) Nanostructured foam w/ tunnel ionisation: **C**: 0-times ionised, **Al**: 3-times ionised

(c) Nanostructured foam w/o tunnel ionisation: **C**: 4-times ionised, **Al**: 3,5-times ionised

Snapshot of (a) at 120 fs from simulation start



Snapshot of (b) at 120 fs from simulation start



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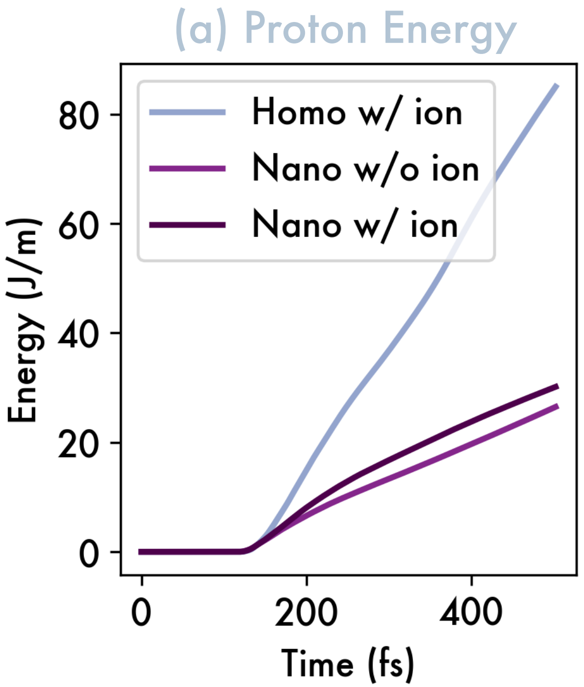
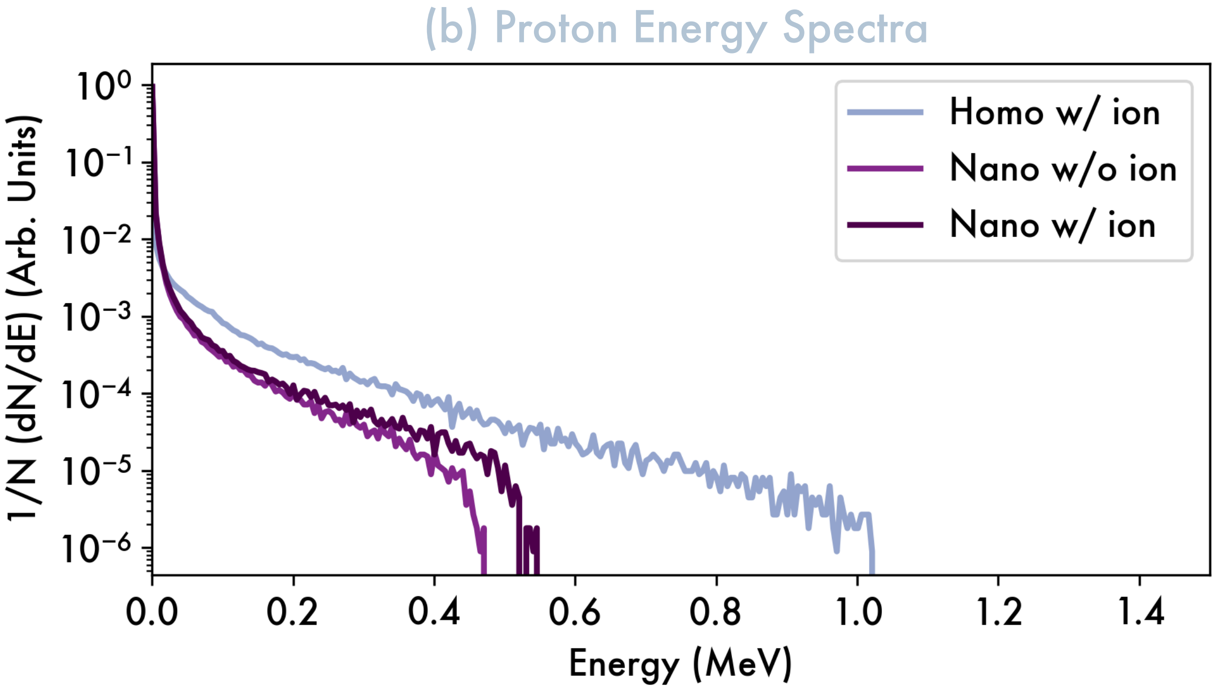
Proton Acceleration from sub-TW Lasers with DLTs





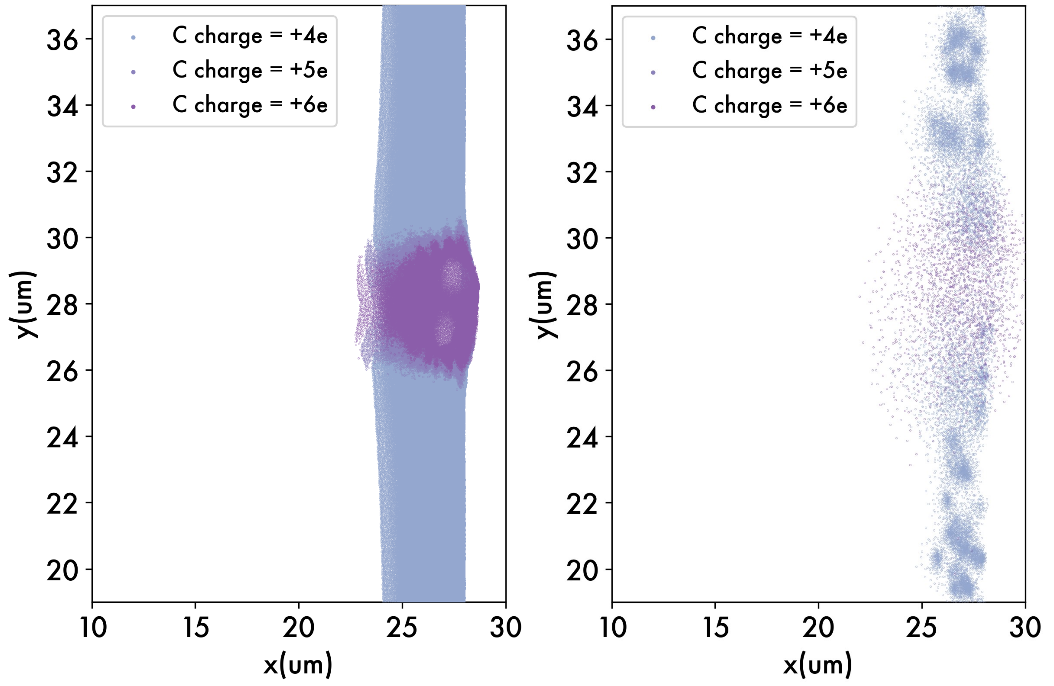
- Reduction of **maximum proton energy** with nanostructure
- Reduction of **total proton energy** with nanostructure

- Increase in laser energy **conversion efficiency** when tunnel ionisation accounted for

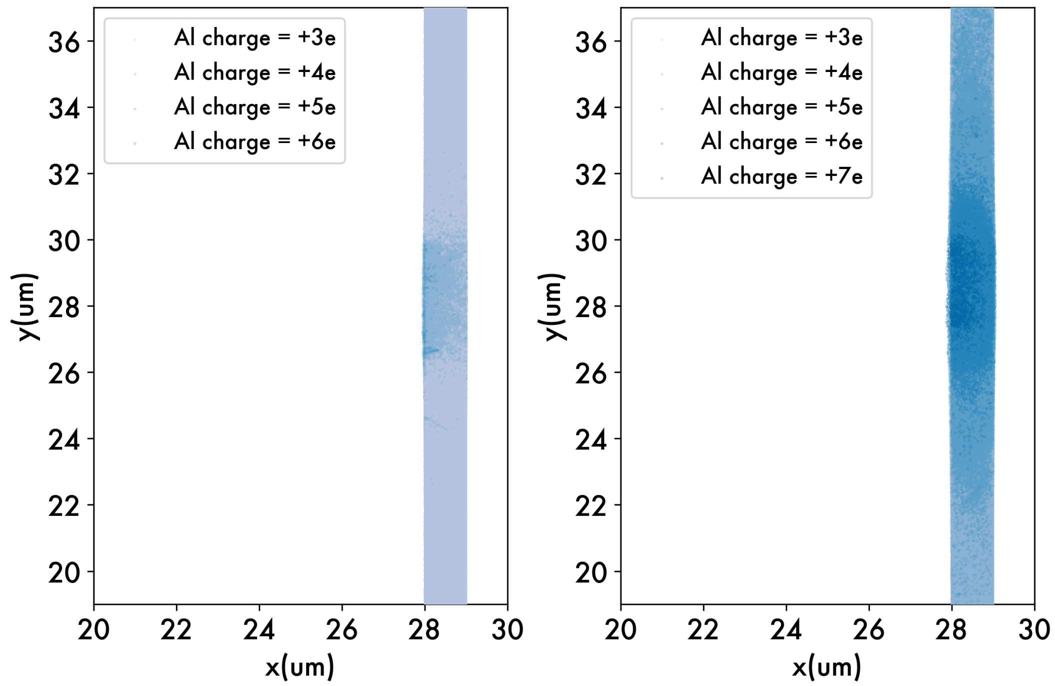
Ambrogioni K., *Numerical Modelling of Laser-Driven Proton Acceleration with Nanostructured Targets and TW-Class Lasers*, MSc. Thesis (2023)

Proton Acceleration from sub-TW Lasers with DLTs

Scatter plot of foam (C) macroions ionisation level of (a) and (b) at 500 fs from simulation start



Scatter plot of solid foil (Al) macroions ionisation level of (a) and (b) at 500 fs from simulation start

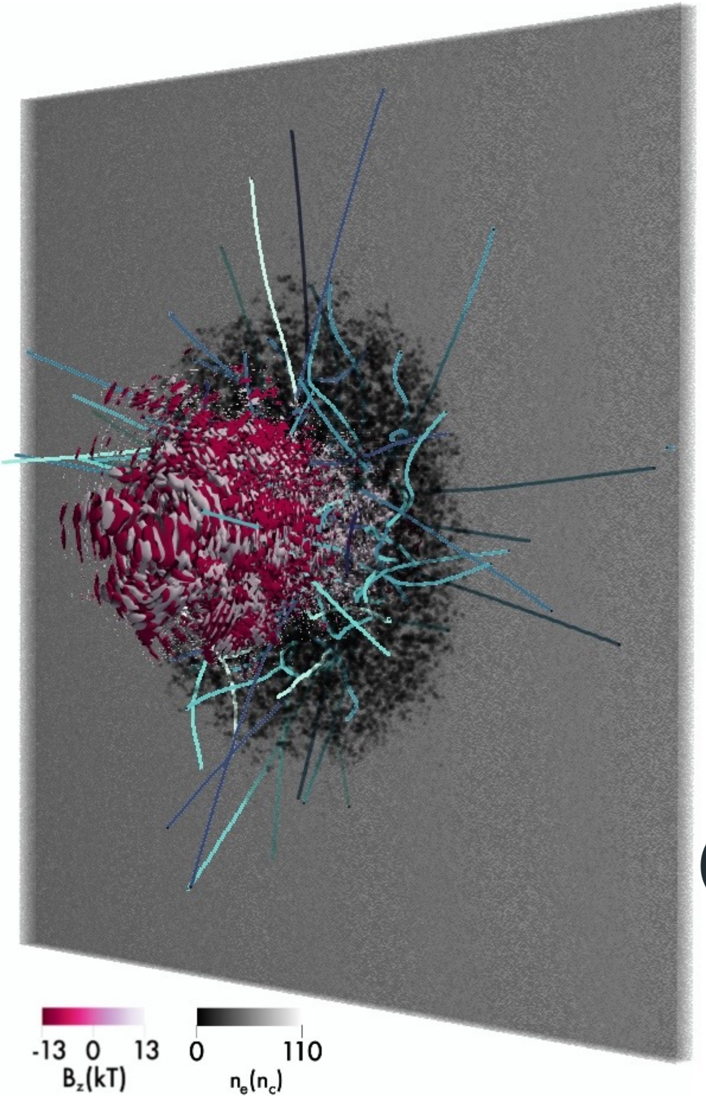


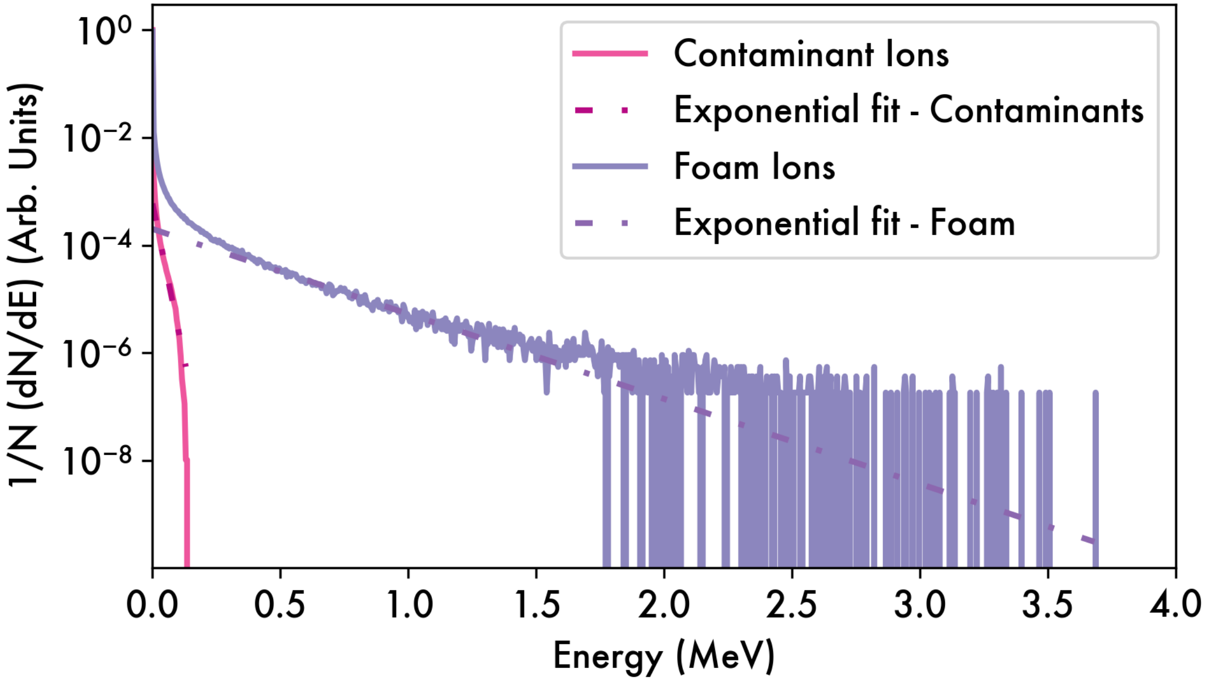
Almost no influence on foam ionisation:
highly ionised in both cases

Great influence on solid foil ionisation:
increase of ionisation level with nanostructure

Ambrogioni K., *Numerical Modelling of Laser-Driven Proton Acceleration with Nanostructured Targets and TW-Class Lasers*, MSc. Thesis (2023)

Proton Acceleration from sub-TW Lasers with DLTs

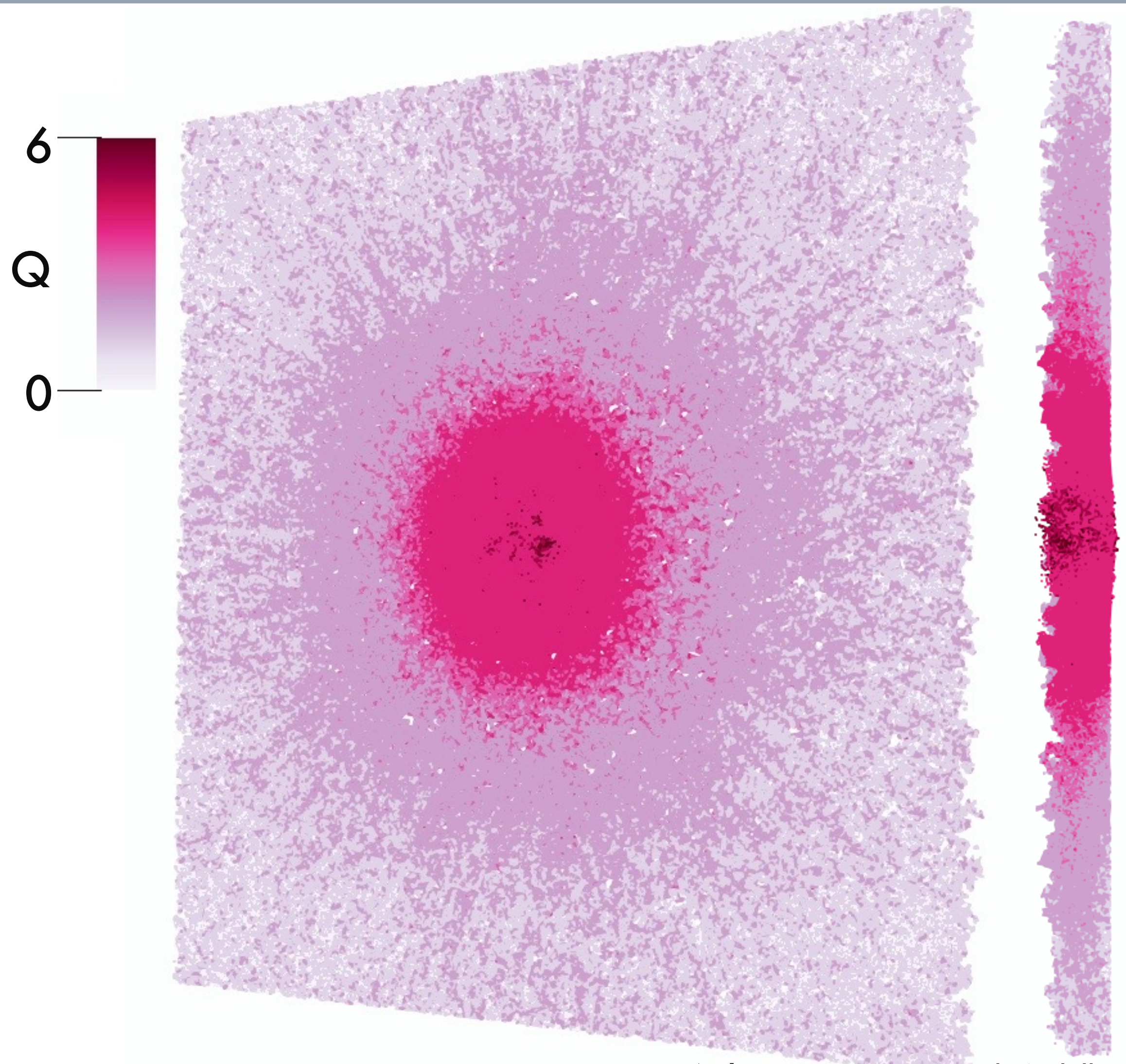




- Low maximum proton energy (~100 keV) with laser energy conversion efficiency in proton energy below 1%
- High laser energy conversion efficiency in foam ions (~20%) with maximum ion energy above MeV (~4 MeV)

Ambrogioni K., *Numerical Modelling of Laser-Driven Proton Acceleration with Nanostructured Targets and TW-Class Lasers*, MSc. Thesis (2023)

Proton Acceleration from sub-TW Lasers with DLTs



Foam ionisation

Almost complete ionisation of the foam (5-times-ionised) in laser channel

Dimensionality effects in ionisation

Overall degree of ionisation lower in 3D with respect to 2D relevant simulation

Ambrogioni K., *Numerical Modelling of Laser-Driven Proton Acceleration with Nanostructured Targets and TW-Class Lasers*, MSc. Thesis (2023)

Pair-Production via Non-Linear Breit-Wheeler in DLTs

2D simulation for DLT in Smilei on CINECA - Galileo100 neglecting nanostructure, including Non-linear Inverse Compton Scattering for photon production and Non-Linear Breit-Wheeler pair production. The target was simulated as a completely ionised plasma.

Simulation Parameters	
Box Size [x;y] (μm)	[70;50]
Points per μm [x;y]	[64;64]
CFL	0,95
Duration (fs)	350
Processing Units	1536
Boris pusher, PML/Absorbing in x, Periodic/Periodic in y, Load Balancing	

Laser Parameters	
a_0	150
Intensity (W/cm²)	4,8 x 10^{22}
Laser Spot (μm)	3.0
Wavelength (μm)	0,8
Pulse Duration (fs)	30
Polarisation	Linear (y-plane)
Incidence Angle	0°
Shape in Time	Gaussian
Shape in Space	Gaussian

Foam Parameters	
Element	C
Density (n_c) [e;i]	[2,0;0,33]
Particles per Cell [e;i]	[5;1]
Thickness (μm)	15,0

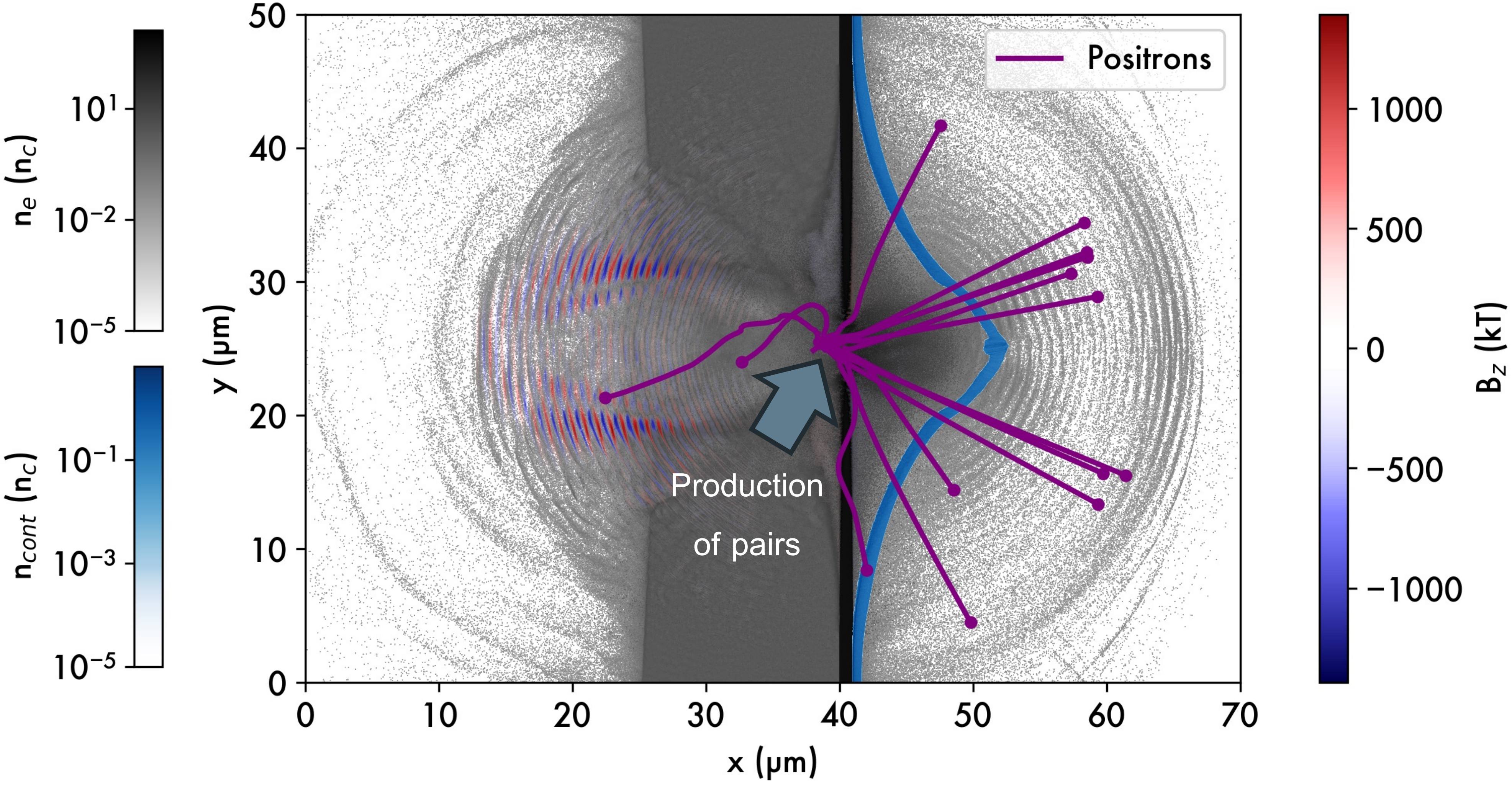
Photon Parameters	
Photon Sample	3
Photon Threshold	$2m_ec^2$

Solid Foil Parameters	
Element	Al
Density (n_c) [e;i]	[450;34,6]
Particle per Cell [e;i]	[30;6]
Thickness (μm)	1,0

Contaminant Layer Parameters	
Element	H
Density (n_c) [e;i]	[10;10]
Particle per Cell [e;i]	[100;100]
Thickness (μm)	0,05

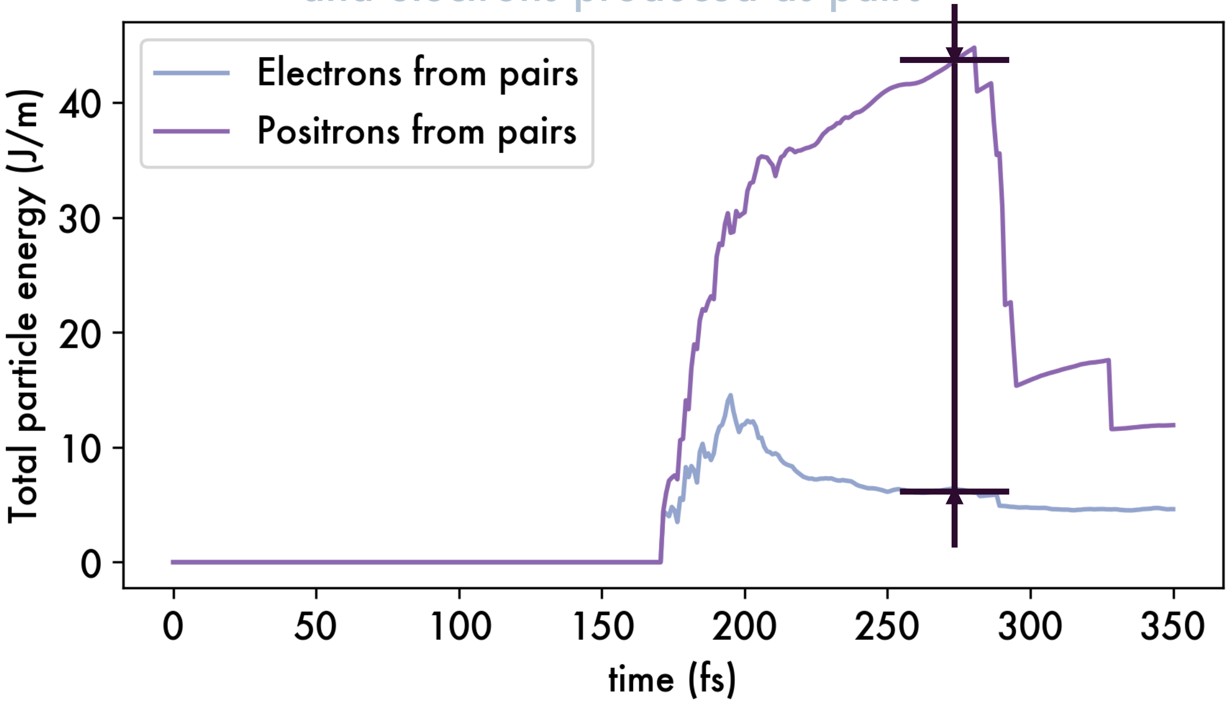
Monaco L. F. C., *Numerical Study of Positron Production in Laser-Plasma Interaction with Double-Layer Targets via Non-linear Breit-Wheeler Process*, MSc. Thesis (in-progress)

Pair-Production via Non-Linear Breit-Wheeler in DLTs



Pair-Production via Non-Linear Breit-Wheeler in DLTs

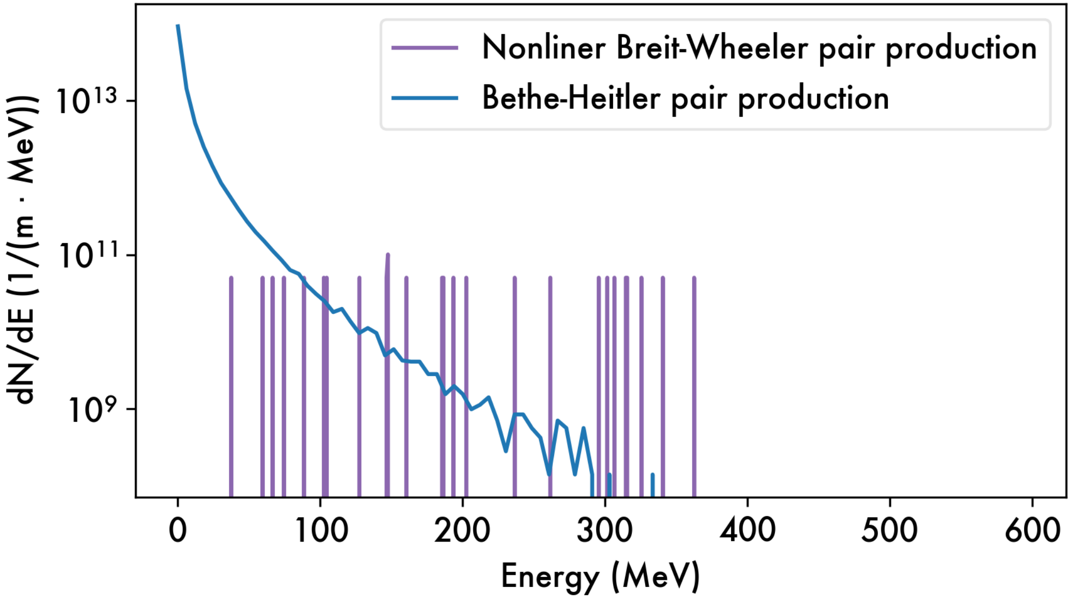
Energy evolution of total energy of positrons and electrons produced as pairs



Noticeable **acceleration of positrons** due to the sheath field behind the target

Work in progress...

Monte Carlo Simulations to evaluate Bethe-Heitler and Non-Linear Breit-Wheeler contributions in pair production with a 1mm-thick Pb solid foil

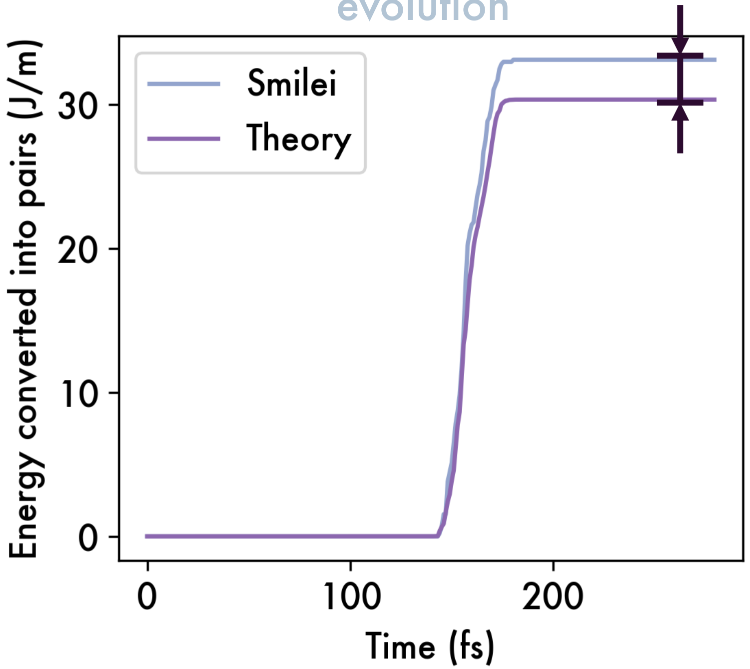


Pair-Production via Non-Linear Breit-Wheeler in DLTs

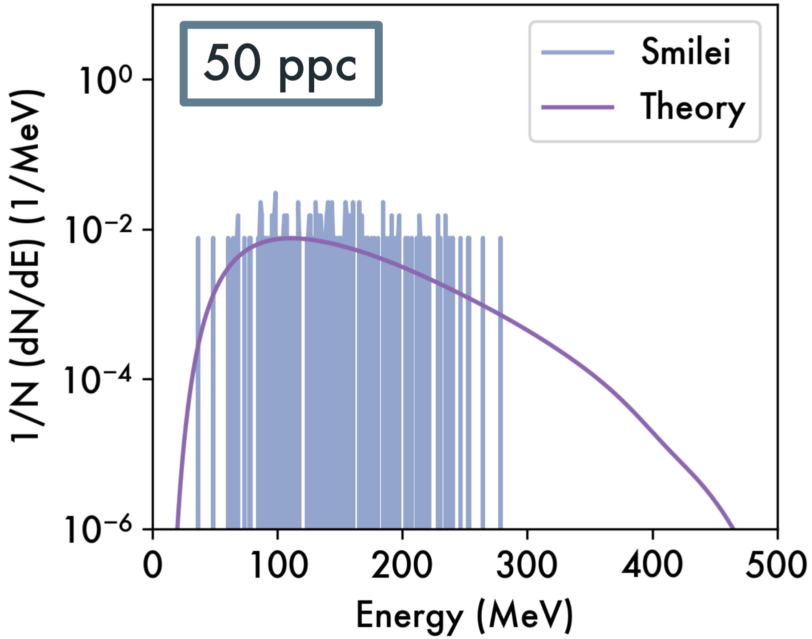
Analytical shape of positron spectrum from Breit-Wheeler:

$$\frac{dN_{e^+}}{dE_{e^+}} = \frac{\alpha}{\sqrt{3}\pi\hbar}\int_{t_0}^{t}\sum_{E_\gamma > 2m_ec^2 + E_{e^+}}\left\{\frac{w_\gamma}{\gamma_\gamma(\gamma_\gamma - 2)}\left[\int_y^{+\infty} K_{1/3}\left(\frac{2}{3}x\right)dx - (2-\chi_\gamma y)K_{2/3}\left(\frac{2}{3}y\right)\right]\right\}dt$$

(a) Total energy of pairs evolution



(b) Positron spectrum at the end of simulation



where: $y = \dfrac{\chi_\gamma}{\chi + (\chi_\gamma - \chi_+)}$,

$$\chi_+ = \frac{E_{e^+}\chi_\gamma}{(\gamma_\gamma - 2)m_ec^2}, \qquad \gamma_\gamma = \frac{E_\gamma}{m_ec^2}.$$

Little discrepancy between simulation and theory in **total energy**

Bad reproduction of the **energy spectrum** due to sampling choices

Monaco L. F. C., *Numerical Study of Positron Production in Laser-Plasma Interaction with Double-Layer Targets via Non-linear Breit-Wheeler Process*, MSc. Thesis (in-progress)

Pair-Production via Non-Linear Breit-Wheeler in DLTs

2D simulations for DLT in Smilei) on CINECA - Galileo100 neglecting nanostructure, including Non-linear Inverse Compton Scattering for photon production and Non-Linear Breit-Wheeler pair production. The target was simulated as a completely ionised plasma.

Simulation Parameters	
Box Size [x;y] (μm)	[70;50]
Points per μm [x;y]	[64;64]
CFL	0,95
Duration (fs)	350
Processing Units	1536
Boris pusher, PML/Absorbing in x, Periodic/Periodic in y, Load Balancing	

Laser Parameters	
a_0	150
Intensity (W/cm^2)	4,8 x 10^{22}
Laser Spot (μm)	3.0
Wavelength (μm)	0,8
Pulse Duration (fs)	30
Polarisation	Linear (y-plane)
Incidence Angle	0°
Shape in Time	Gaussian
Shape in Space	Gaussian

Foam Parameters	
Element	C
Density (n_c) [e;i]	[2/6/12; 0,5/1/2]
Particles per Cell [e;i]	[4/12/12; 1]
Thickness (μm)	12,0-39,0

Photon Parameters	
Photon Sample	3
Photon Threshold	2

Solid Foil Parameters	
Element	Al/Au/Pb
Density (n_c) [e]	[100-586]
Particle per Cell [e;i]	[30;6]
Thickness (μm)	2,0/5,0

Contaminant Layer Parameters	
Element	H
Density (n_c) [e;i]	[10;10]
Particle per Cell [e;i]	[100;100]
Thickness (μm)	0,05

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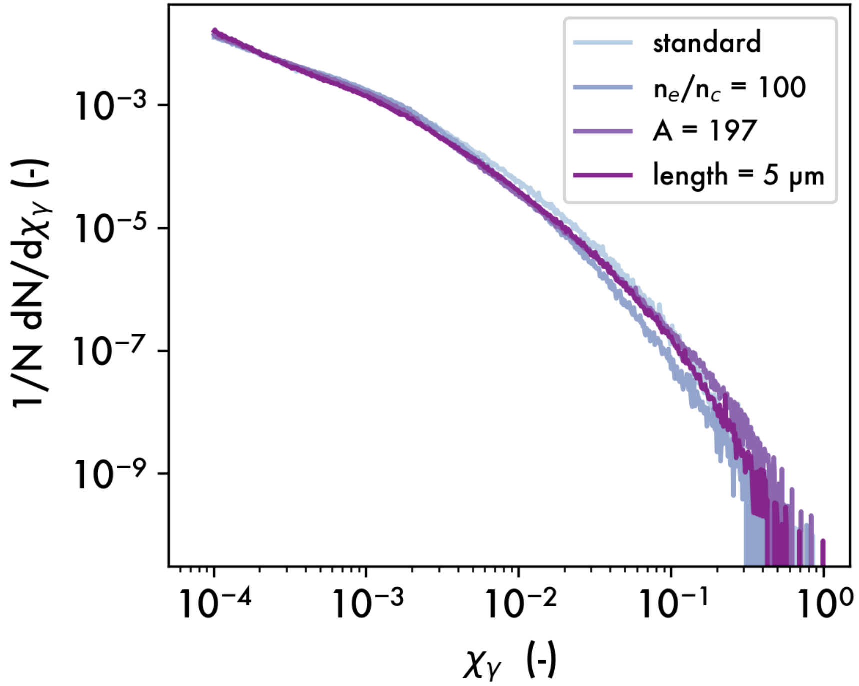
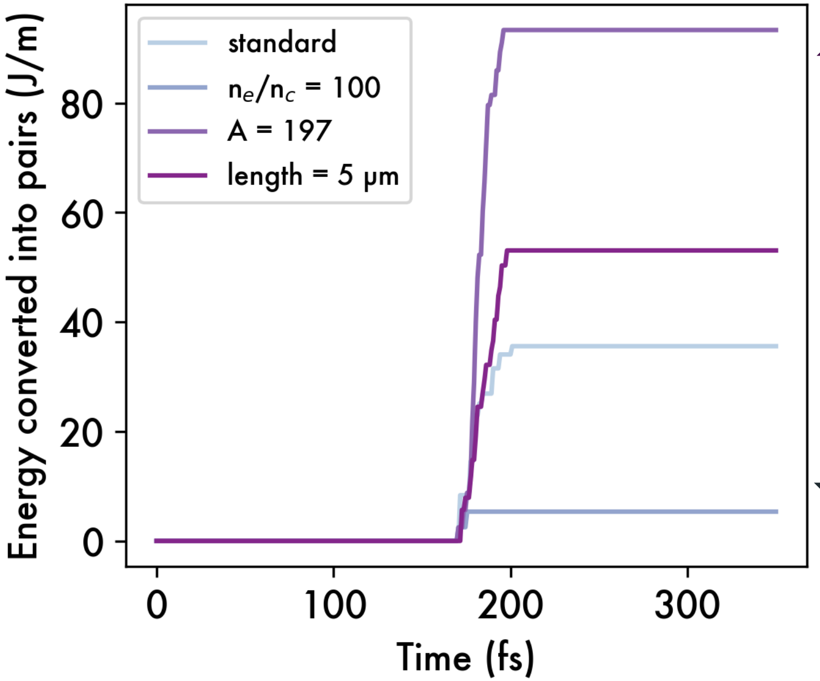
Pair-Production via Non-Linear Breit-Wheeler in DLTs

(a) Photon quantum parameter distribution



(b) Total energy of pairs evolution



Effects of ion mass

Effects of thickness

Effects of density

The **increase in the laser reflection** guarantees a higher photon quantum parameter

The increase in photon quantum parameter is reflected in **laser conversion efficiency into pairs**

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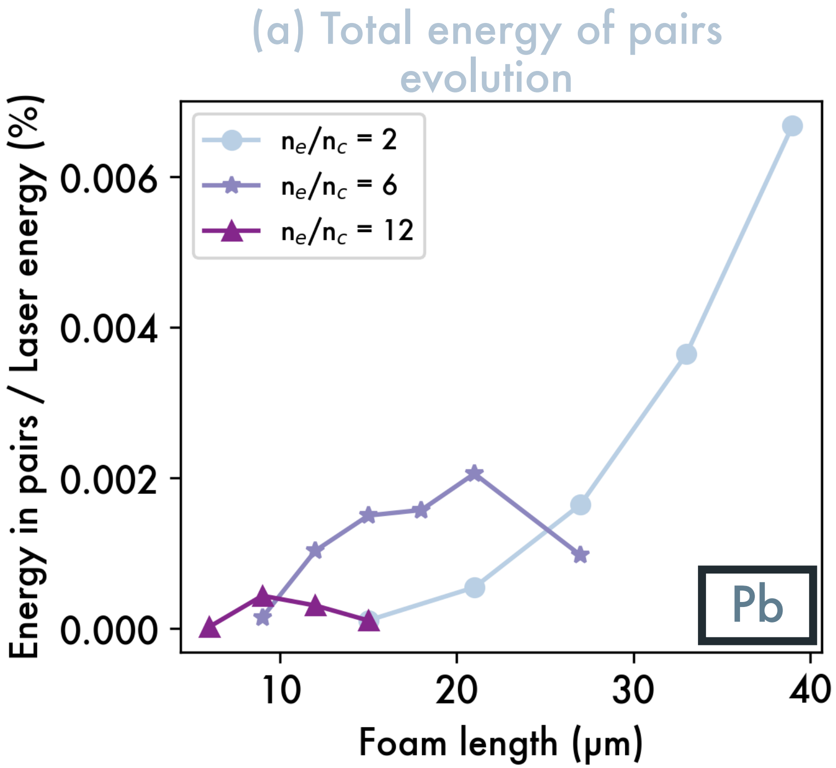
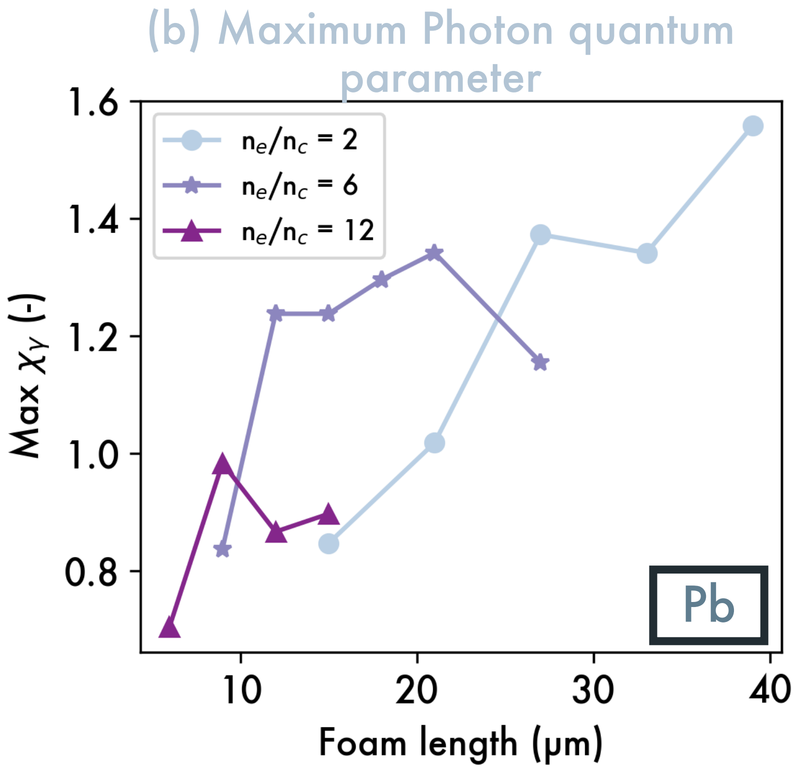
Pair-Production via Non-Linear Breit-Wheeler in DLTs





- Increase in **conversion efficiency** into pairs with **decreasing foam density**
- Optimal thickness of the foam depending **on absorbed/reflected laser components**

Maximum photon quantum parameter following a behaviour similar to the one of **conversion efficiency**

Monaco L. F. C., *Numerical Study of Positron Production in Laser-Plasma Interaction with Double-Layer Targets via Non-linear Breit-Wheeler Process*, MSc. Thesis (in-progress)

Conclusions and Perspectives

Numerical investigation of laser-plasma interaction is **fundamental** to capture the physics of the acceleration process. Integrated **PIC-Monte Carlo Codes** such as Smilei) are necessary to study **physical effects** relevant to radiation sources.

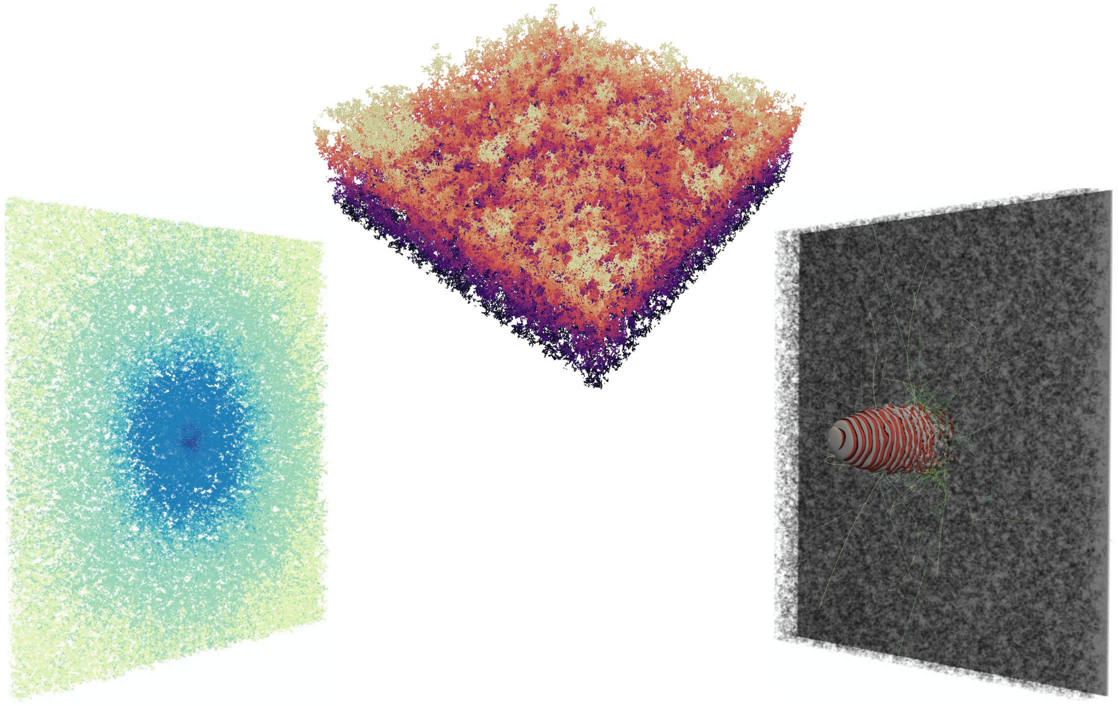
- Specifically **optimised DLTs** can be used to generate **different radiation fields**
- **Compact sources** (up to table-top) can be used by employing the appropriate configuration
- DLTs allow **production of pairs** during laser-plasma interaction with **ultra-high-intensity lasers**
- Smilei) was shown **versatile** in allowing modelling for highly different radiation sources

Perspectives

- Study of possible design of **compact sources** for applications in **cultural heritage**
- Solution to the problem on **the statistics of Breit-Wheeler** mechanism
- Studies on pair production with **Bethe-Heitler mechanism** at lower laser intensity

4th Smilei user & training workshop

8-10 November 2023, ELI Beamlines



Thanks for your attention!

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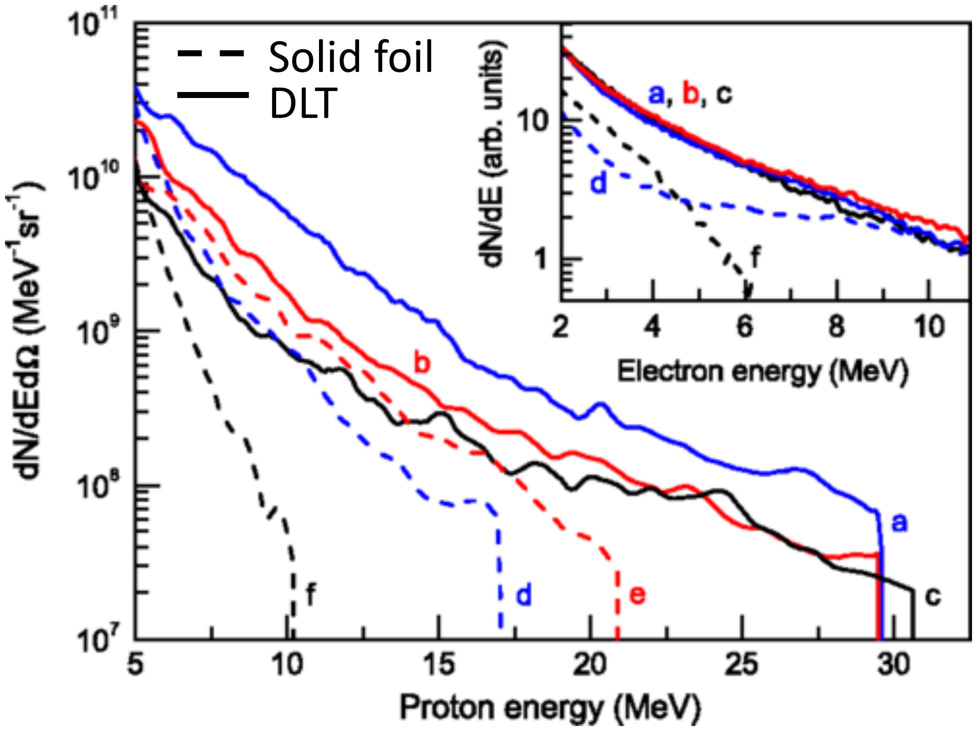
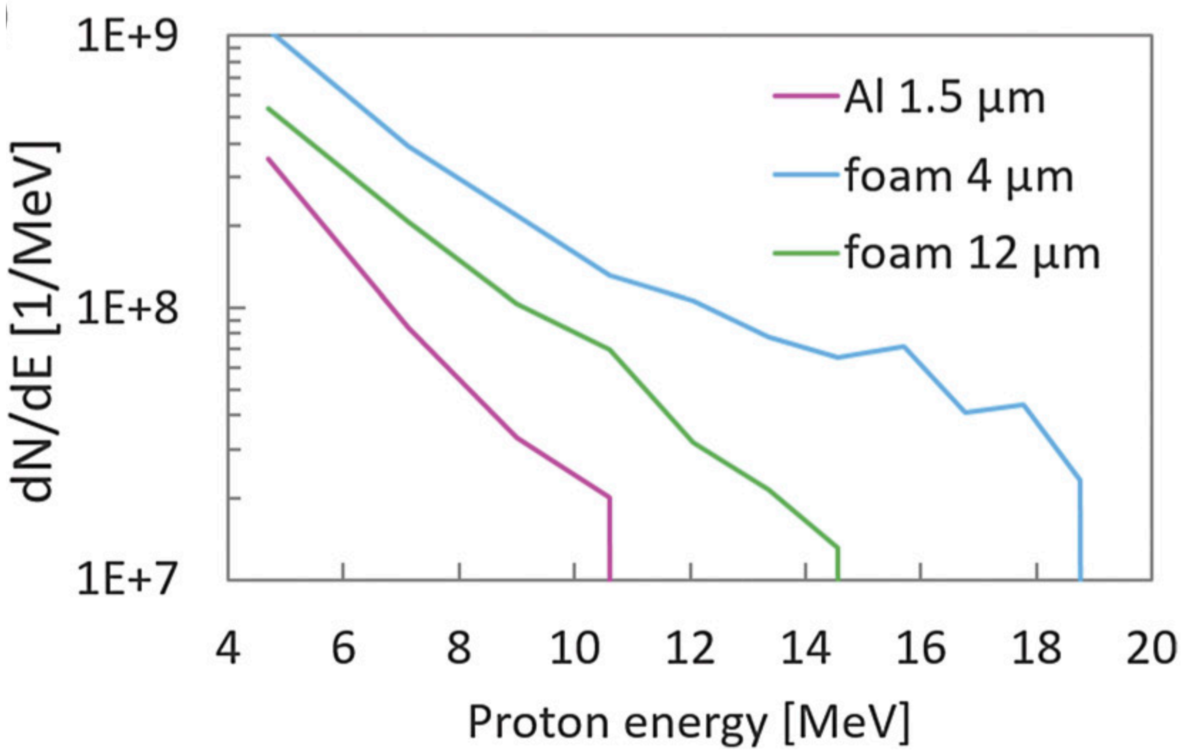
Experimental Data of Laser-Driven Proton Acceleration with DLTs



M. Passoni et al., *Toward high-energy laser-driven ion beams: Nanostructured double-layer targets* , Physical Review Acc. and Beams, *19, 061301* (2016)



I. Prencipe et al., *Efficient laser-driven proton and Bremsstrahlung generation from cluster-assembled foam targets* , New Journal of Physics, *23, 093015* (2021)