Numerical study of high-energy photon emission in double-layer targets

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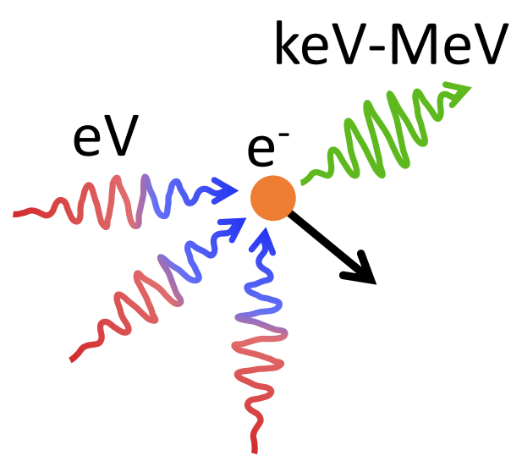
Introduction: Laser Interaction with Double-Layer Target

Laser pulse of **fs duration**, **µm focal spot** and $a_0 = \frac{eE_0}{m_e \omega_0 c} > 1$ interacting with a **Double-Layer Target** (DLT) made of a **solid substrate** $\sim$ **1 µm** and a **nanostructured foam** $\sim$ **10 µm** grown with Pulsed Laser Deposition [1] with average density $\sim n_c = \frac{m_e \omega_0^2 \varepsilon_0}{e^2}$ (few mg/cm^3).

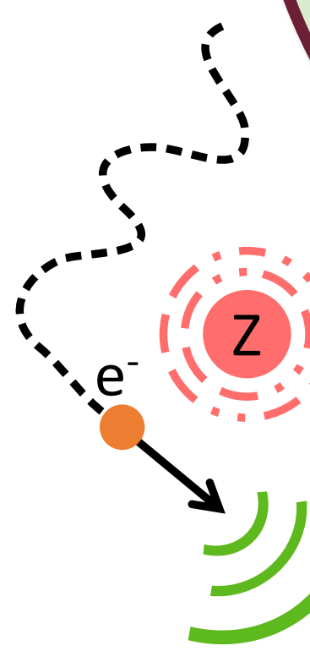
Relevant processes of the interaction are [2]:

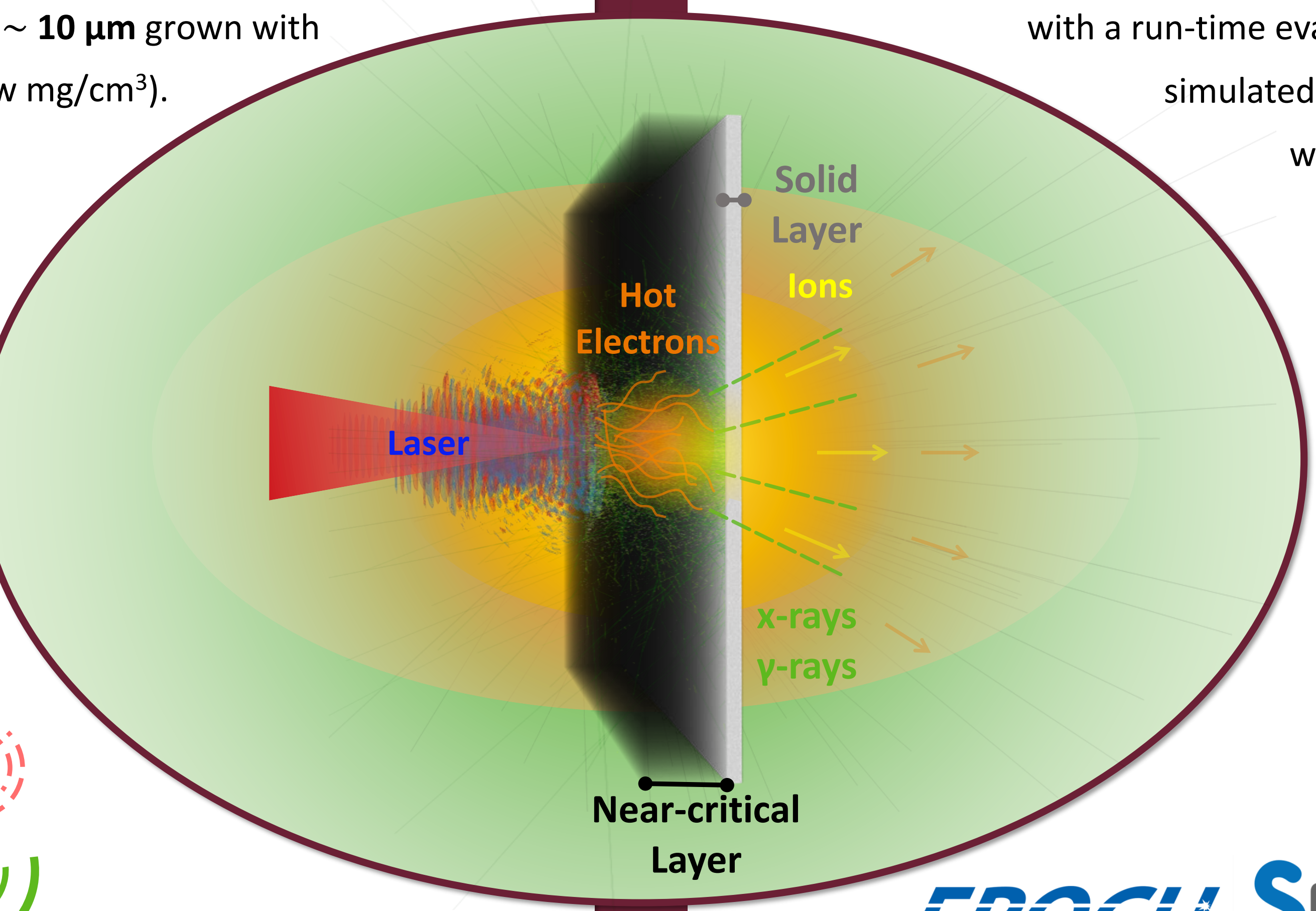
- the enhanced laser-plasma coupling around near-critical density
- the relativistic laser self-focusing inside the foam
- the laser reflection on the substrate
- the acceleration of electrons towards the substrate.

They result in the **boosted emission of high-energy photons** in the **keV-MeV** range through:



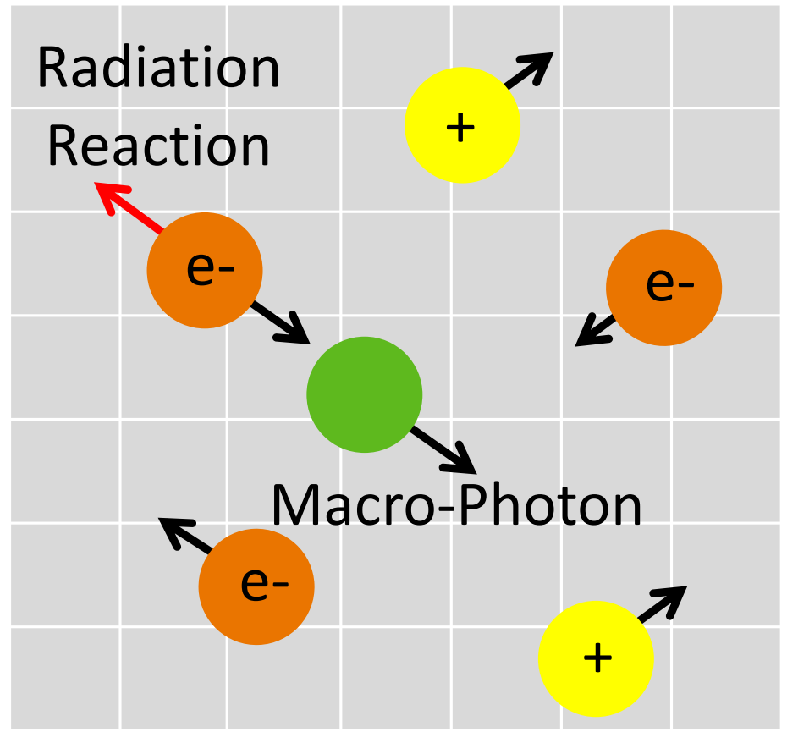
Non-linear Inverse Compton Scattering (NICS), **a synchrotron-like** emission due to the presence of strong fields [3], and **Bremsstrahlung**, due to the electron scattering in the Coulomb field of target nuclei [4].

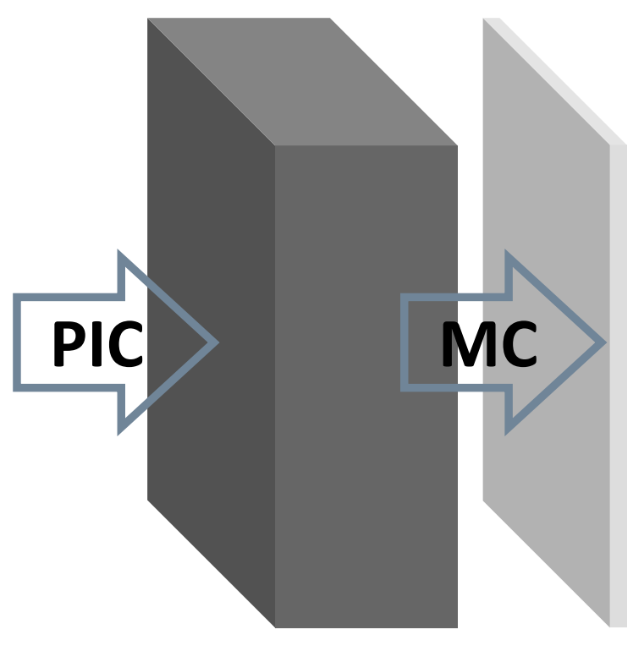




Methods: Particle-in-cell and Monte Carlo

The numerical study consists of **Particle-In-Cell** (PIC) simulations with a run-time evaluation of photon emission [5]. The simulated scenario is a linearly polarised laser with λ = 0.8 µm interacting at normal incidence with a **carbon foam** of variable density and thickness on top of a solid **aluminium substrate**. In alternative, feed a **standard Monte Carlo** code [6] with the electron distribution computed by the PIC code or estimate the emission with **analytical formulas.**





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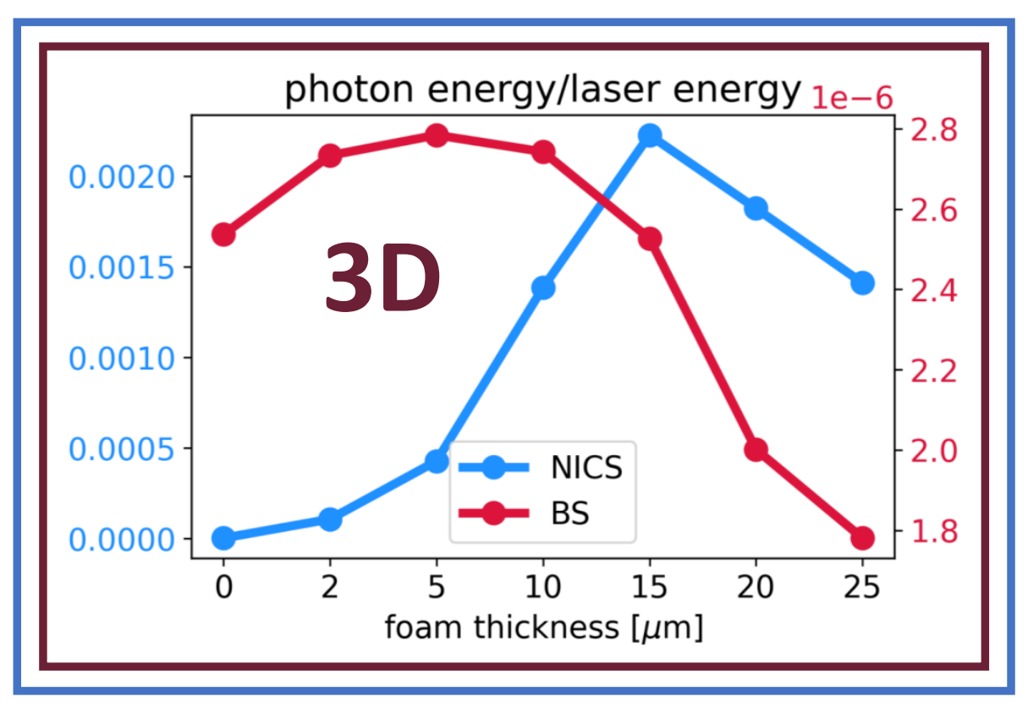
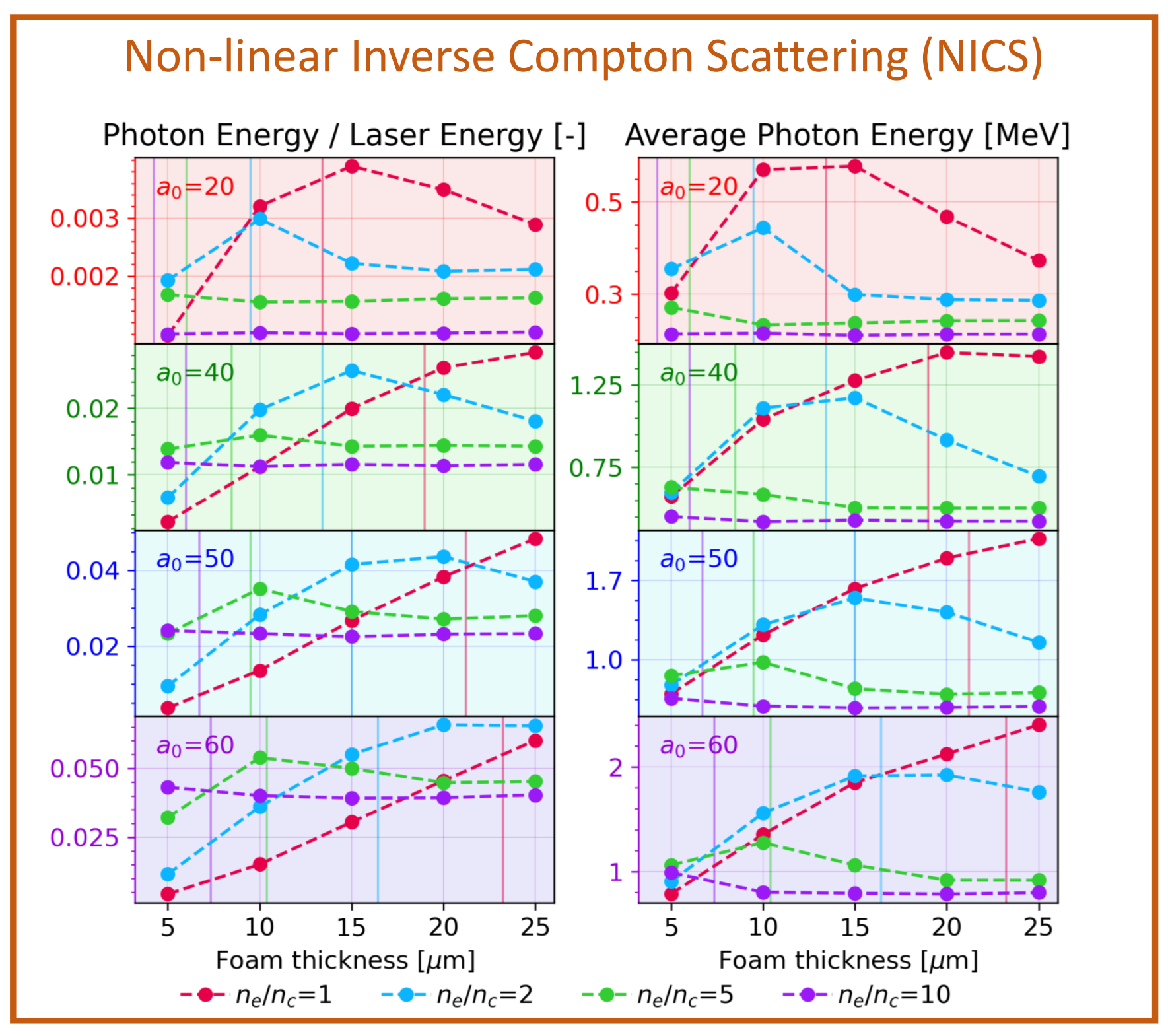
Results of Simulations: Laser and Target Optimization for Photon Emission

2D [7,8] and 3D scans to evaluate optimal target and laser parameters. a$_0$ = 20-40-50-60/20, Laser waist = 3 µm, FWHM = 20/30 fs, Substrate Density= 450/80 n$_c$ & Thickness= 2/1 µm.

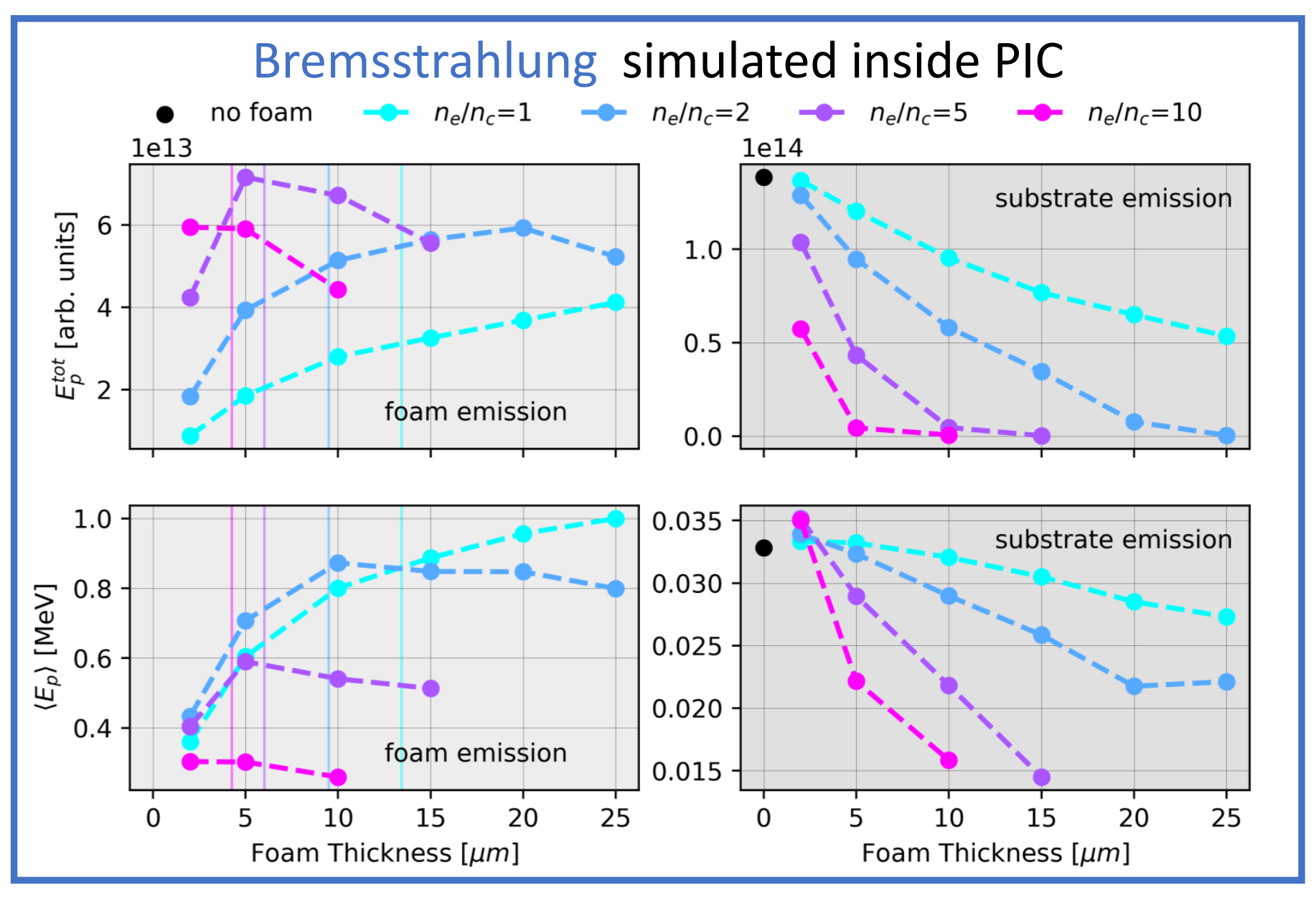
The **self-focusing length** $f \approx \omega_0 \sqrt{\frac{n_c}{n_e}} \left(1 + a_0^2/2\right)^{1/2}$ helps identifying the range of optimal foam thickness. Thick low-density foams enhance high-energy emission. Thin foams enhance recirculation and low-energy bremsstrahlung.



Non-linear Inverse Compton Scattering (NICS)



Bremsstrahlung simulated inside PIC

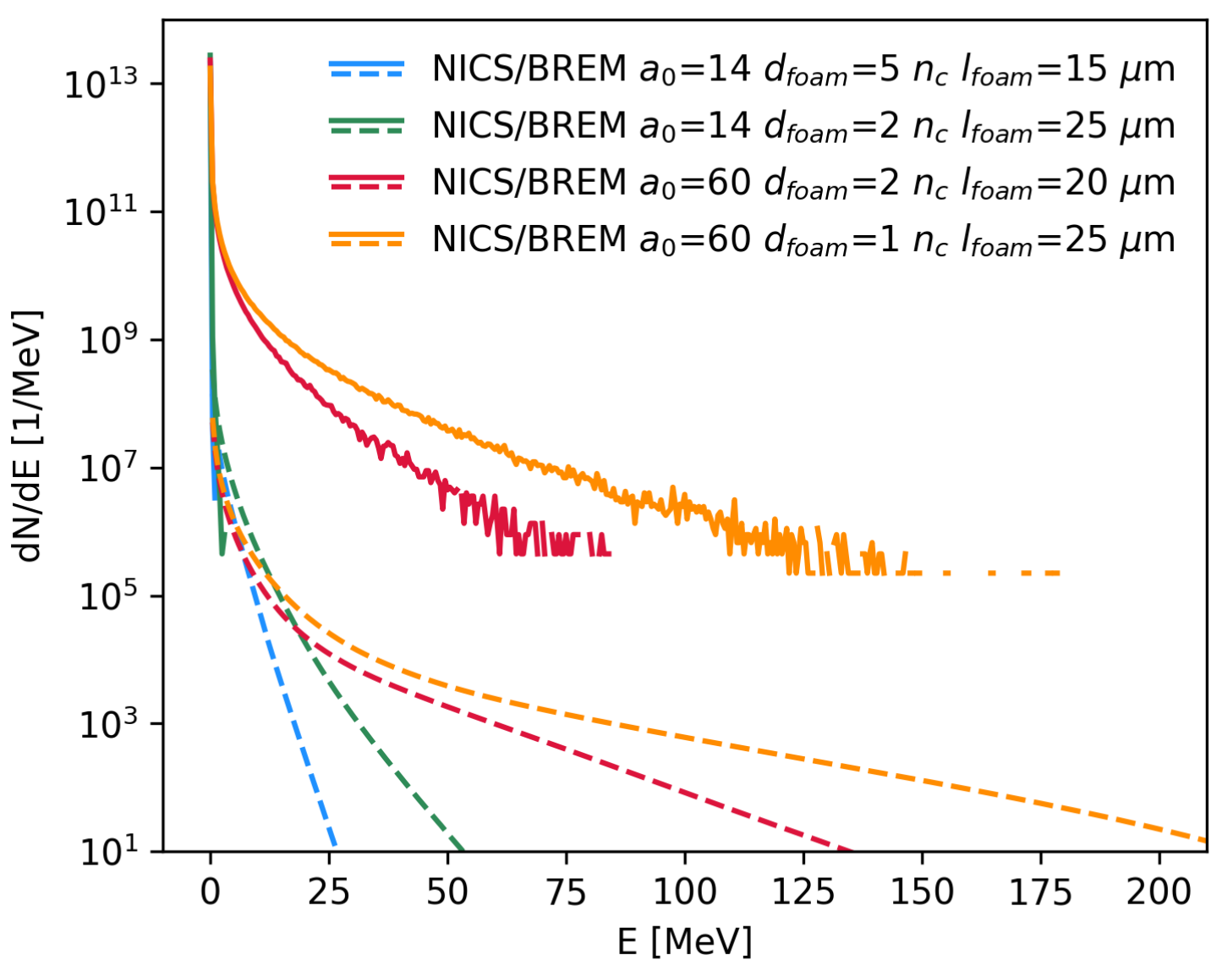


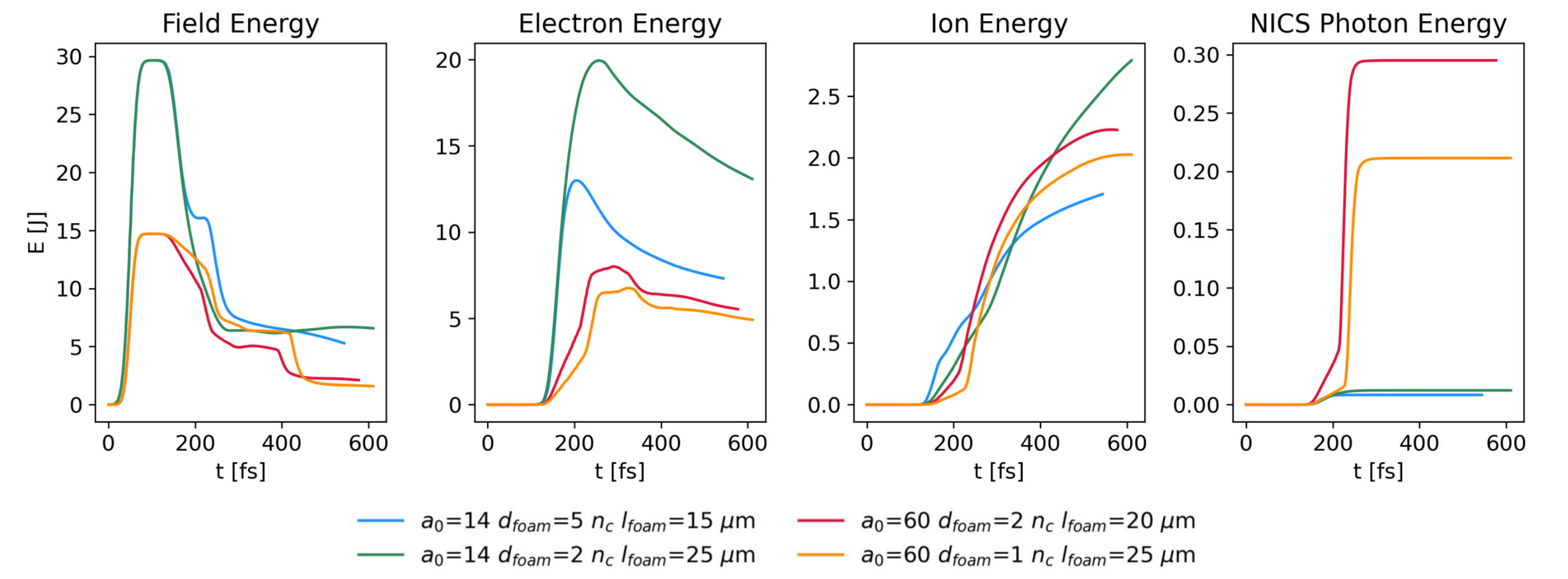
3D simulations to evaluate experimental conditions. a$_0$ = 14/60, Laser waist = 12/2.16 µm, FWHM = 25/30 fs, Substrate Density= 80 n$_c$ & Thickness= 2 µm. NICS is simulated inside the PIC, and Bremsstrahlung spectrum is estimated with:

$$\boxed{\frac{dN}{dE_p} = n_i \int_{t_0}^{t_1} dt \int_{E_p}^{\infty} dE_e \left[\frac{dN}{dE_e} v_e \frac{aZ^2}{E_p} \left(1 - \frac{bE_p}{E_e}\right) \right]}$$

where a= 11·10^{-31} m^2 and b=0.83.

NICS emission dominates for a$_0$ = 60.





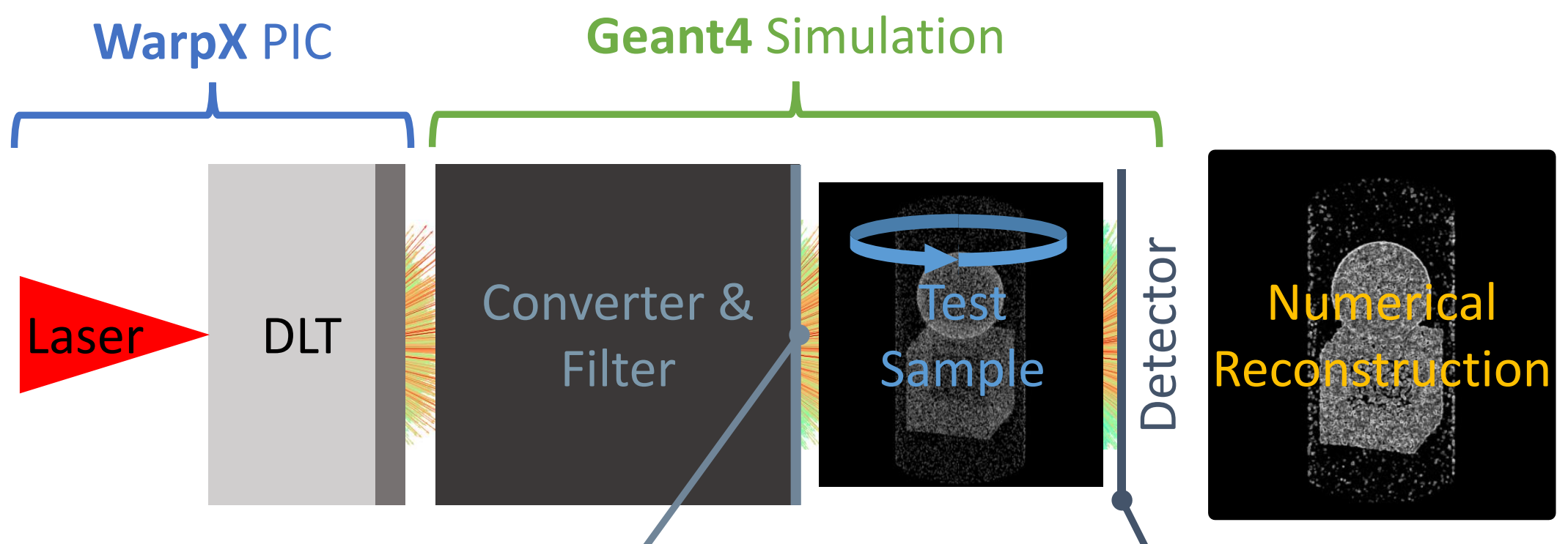
Applications, Perspectives, and Conclusions

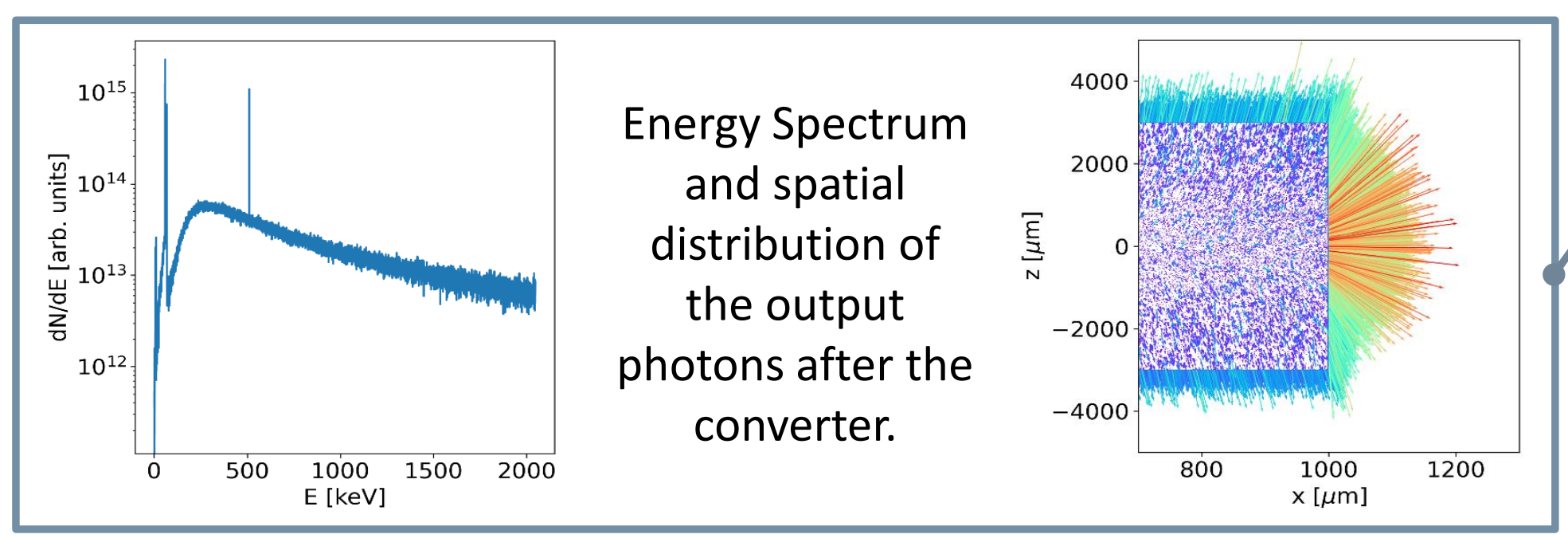
Tunable Laser-Driven High-Energy Photon Sources can have various **applications** like radiography, tomography, interrogation of materials, photo-nuclear activation analysis, diagnostic for laser-plasma, and QED plasma physics exploration. To prove their feasibility, exploring NICS and Bremsstrahlung in **experimental campaigns** is essential. DLT and laser parameters can be used to **select the process of interest**. At relatively low laser intensities, when Bremsstrahlung is more relevant, **target nanostructure [9] and ionisation** should be considered for a **complete and accurate modelisation** of laser-plasma interaction.

A possible application:

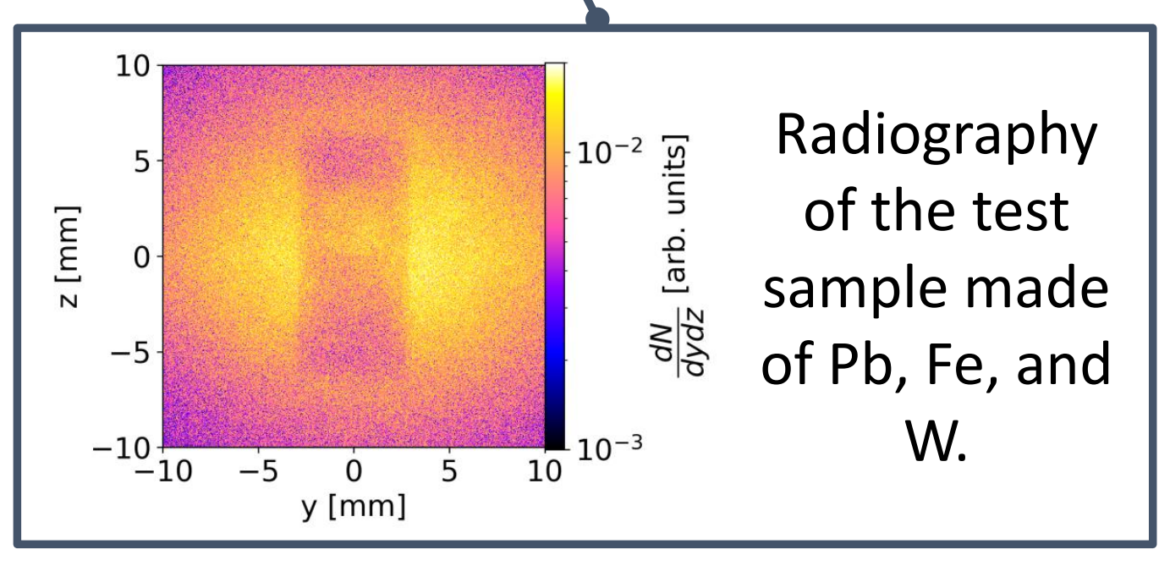
Laser-driven Tomography, 3D imaging by sections using x-rays from a compact and optimised laser-driven source.

a$_0$ = 10, Converter = Tungsten 1mm, Foam Density = 2 n$_c$ & Thickness = 16 µm.



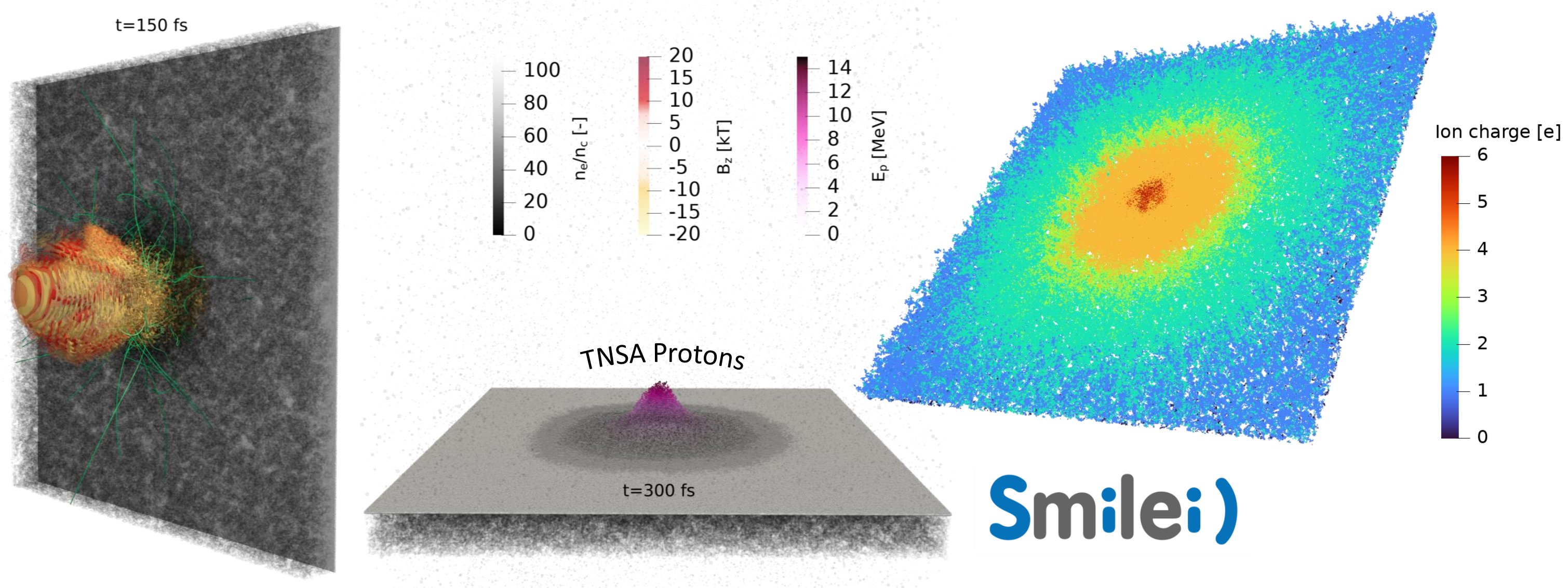


Energy Spectrum and spatial distribution of the output photons after the converter.



Radiography of the test sample made of Pb, Fe, and W.

3D simulations [10] with nanostructured foam of average density 0.95/2.6 n$_c$ and thickness 3/4 µm. a$_0$ = 1.4/10, Laser waist = 2.5 µm, Intensity FWHM = 10/30 fs, Substrate Density= 80 n$_c$ & Thickness= 200 nm/1 µm. Nanostructure and ionisation increase laser absorption at low intensities.



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