21st meeting on Atomic Processes in Plasmas

15-19 May 2023 - Vienna

Numerical investigation of bremsstrahlung in laser-plasma interaction with double-layer targets

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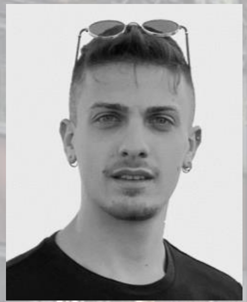

K. Ambrogioni

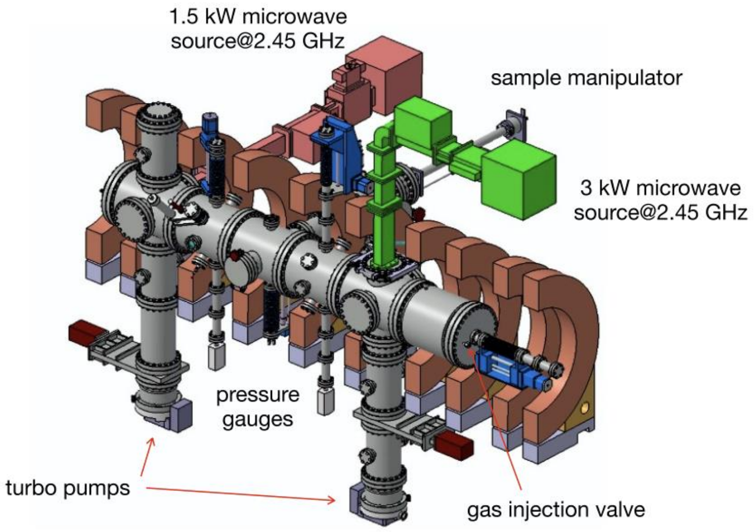

M.S. Galli De Magistris

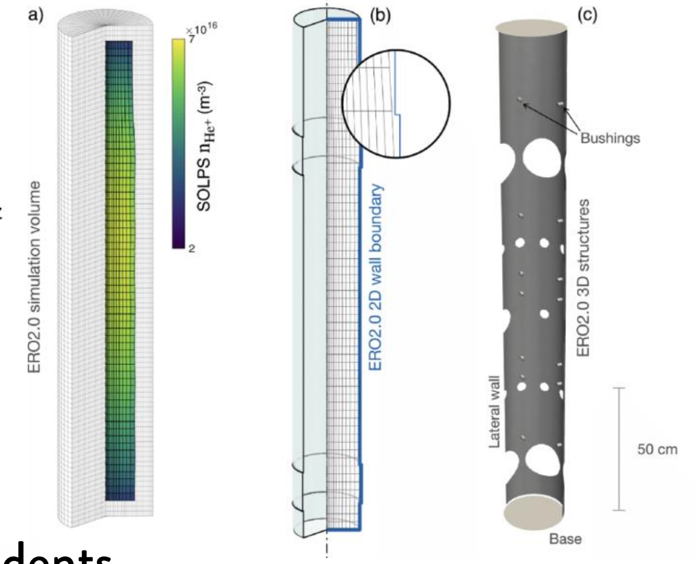
Plasma-Wall Interaction in Fusion Devices

Plasma transport and erosion in the GyM linear device modelled with SOLPS-ITER and ERO2.0 codes.

	Reaction	Type	Database
(1a)	$He + e^- \to He^+ + 2e^-$	EI–H.4	ADAS adf11/scd96
(1b)	$He^+ + e^- \to He^{2+} + 2e^-$		
(2a)	$He + e^- \to He^{(*)} + e^-$	EI–H.10	ADAS adf11/plt96
(2b)	$He^+ + e^- \to He^{+(*)} + e^-$		
(3a)	$He^+ + e^- \to He$	RC–H.4	ADAS adf11/acd96
(3b)	$He^{2+} + e^- \to He^+$		
(4a)	$He^+ + e^- \to He + h\nu$	RC–H.10	ADAS adf11/prb96
(4b)	$He^{2+} + e^- \to He^+ + h\nu$		
(5a)	$He^+ + He \to He + He^+$	CX–H.1–H.3	HYDHEL 5.3.1
(5b)	$He^{2+} + He \to He + He^{2+}$	CX–H.1–H.3	HYDHEL 6.3.1
(6)	$He + He \to He + He$	EL–H.2	AMMONX R-HE-HE

Alberti, G., Tonello, E., Carminati, P., Uccello, A., Bonnin, X., Romazanov, J., Brezinsek, S., & Passoni, M. (2023). Global SOLPS-ITER and ERO2.0 coupling in a linear device for the study of plasma–wall interaction in helium plasma. Nucl. Fusion 63(2), 026020.





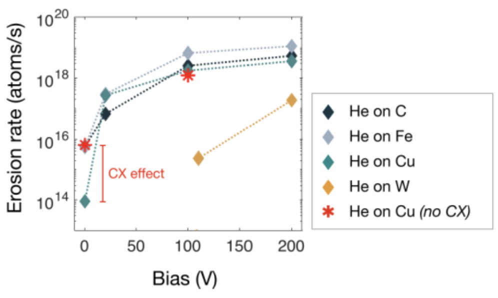


Figure 5. Global erosion rate, computed by ERO2.0 integrating the erosion over the whole modelled surfaces, as a function of the applied bias voltage. Different materials have been selected for the 3D wall elements from which erosion is computed.

PhD Students


G. Alberti

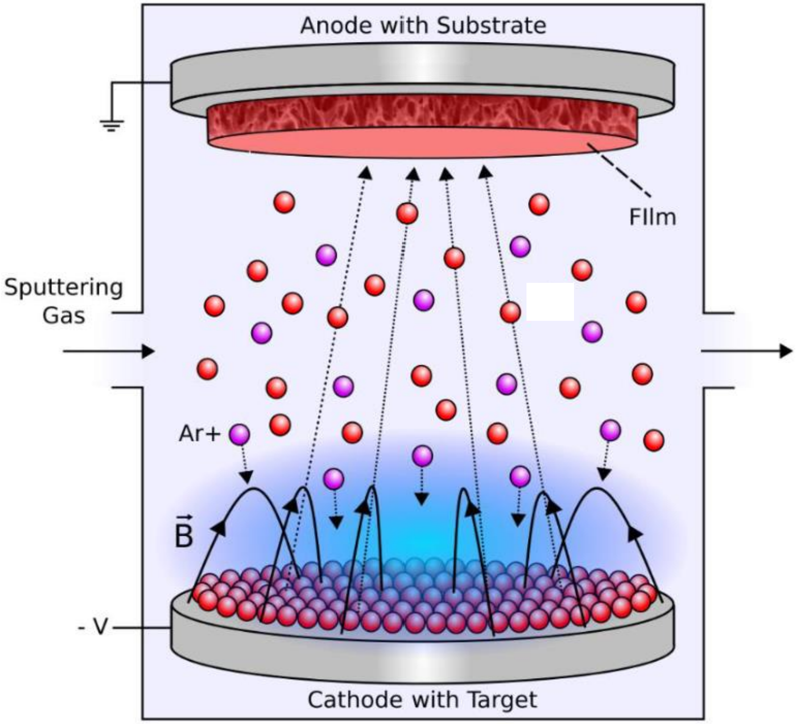

L. Bana


F. Mombelli

Plasma in High-Power Impulse Magnetron Sputtering

Ionization Region Model for the Ar/W System

Reaction	Energy Thr. [eV]
$Ar + e \rightarrow Ar^{+} + 2e$	15.76
$Ar^{m} + e \rightarrow Ar^{+} + 2e$	4.2
$Ar + e \rightarrow Ar^{m} + e$	11.56
$Ar^{m} + e \rightarrow Ar + e$	−11.56
$Ar + e \rightarrow Ar + e$	–
$W + e \rightarrow W^{+} + 2e$	7.98
$W + e \rightarrow W^{*} + e$	0.65
$W + e \rightarrow W + e$	–
$W^{+} + e \rightarrow W^{2+} + 2e$	16.3
$Ar^{m} + W \rightarrow Ar + W^{+} + e$	3.58
$Ar^{+} + W \rightarrow Ar + W^{+}$	–
$Ar + W^{2+} \rightarrow Ar^{+} + W^{+}$	–



Vavassori, D., Mirani, F., Gatti, F., Dellasega, D., & Passoni, M. (2023). Role of magnetic field and bias configuration on HiPIMS deposition of W films. Surf. Coat. Tech., 458, 129343.

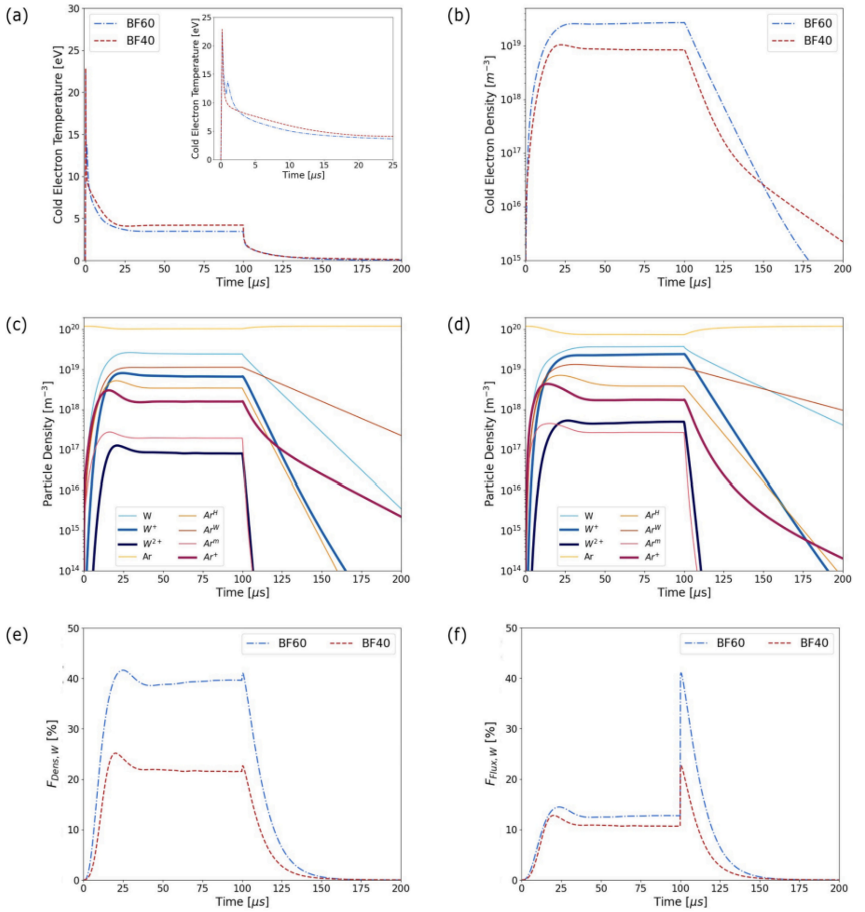


Fig. 2. The temporal evolution of (a) cold electron temperature and (b) cold electron density in the IR for both BF40 and BF60 configurations. The temporal evolution of particle density in the IR for BF40 (c) and BF60 (d) configurations. The ionized species densities are represented with thicker lines. For W sputtered species: the evolution of the ionized fraction (e) in the IR and (f) in the flux from the IR.

Plasma-Based Electric Propulsion

Microwave Electrothermal Thruster operating with nitrous oxide

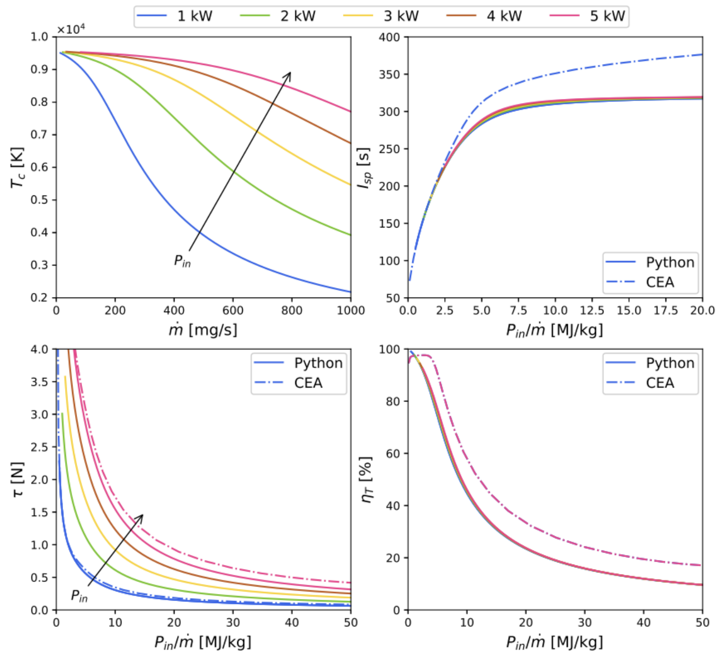
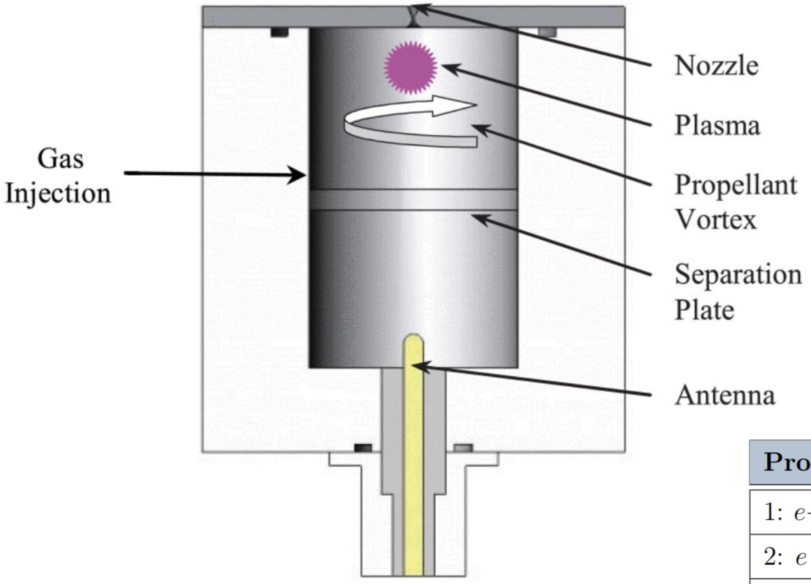


Figure 5.6: UL: chamber temperature vs flow rate. UR: specific impulse vs specific energy. LL: thrust vs specific energy. LR: thrust efficiency vs specific energy. Chamber was simulated to work at 100 kPa and 2.45 GHz, while input power was varied. The dash-dotted line represents the chemical equilibrium model results.



Lauriola, M., & Nava, M. (2023). Feasibility study of a high-performance Microwave Electrothermal Thruster operating with nitrous oxide. Master Thesis.

MSc Student

M. Lauriola

Simplified Model of Plasma in the chamber with Ar

Process	Rate coefficient K $[m^3 s^{-1}]$	U
1: $e{+}Ar^+ \rightarrow e{+}Ar^+$	$2.91 \times 10^{-12} ln\Lambda / T_e^{1.5}$	$3m_e\,(T_e - T_c)\,/M_{Ar}$
2: $e + Ar \rightarrow e + Ar$	$(0.084 + 0.537T_e + 1.192T_e^2) \times 10^{-14}$	$3m_e\,(T_e - T_c)\,/M_{Ar}$
3: $e{+}Ar \rightarrow 2e{+}Ar^+$	$2.34 \times 10^{-14} T_e^{0.59} e^{(-17.44/T_e)}$	$15.76\ eV$
4: $e + Ar \rightarrow e + Ar^*$	$2.48 \times 10^{-14} T_e^{0.33} e^{(-12.78/T_e)}$	$12.14\ eV$

Table 5.1: Rate coefficients and energy (U) lost for: 1) e-i elastic collision, 2) e-n elastic collision, 3) e-impact ionization, and 4) e-impact excitation ($ln\Lambda$ is the *Coulomb logarithm*; the temperatures are expressed in energy units, with T_e in the central column in eV. The expressions are taken from [14, 77].

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

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

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

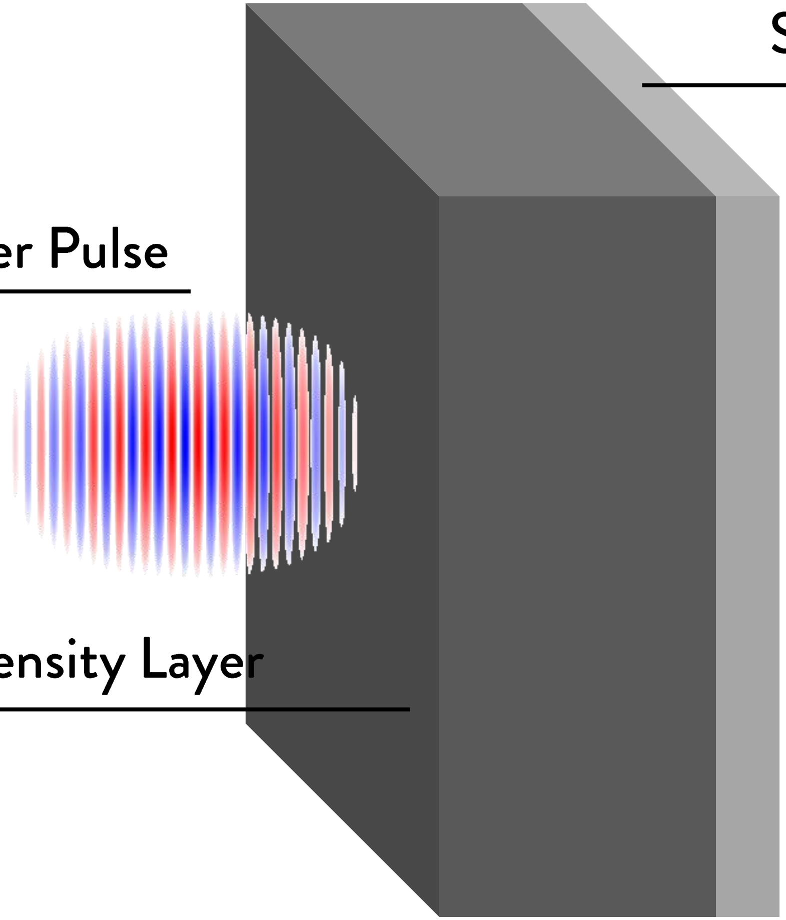
$$a_0 = \frac{eE_0}{m_e \omega c} > 1$$

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

Near-Critical Electron Density

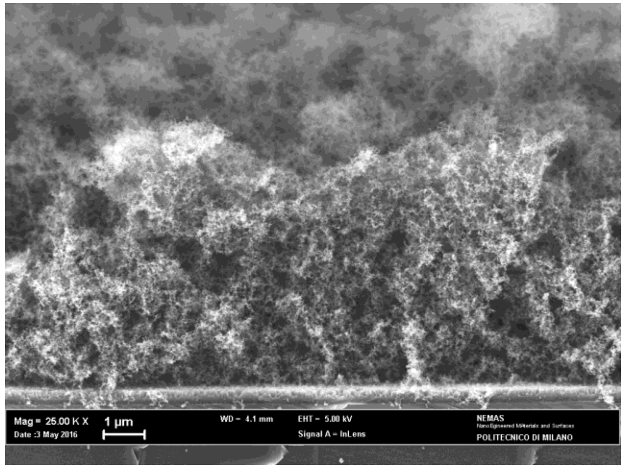
↕

Density of few mg/cm^3



- Solid density
- μm thickness

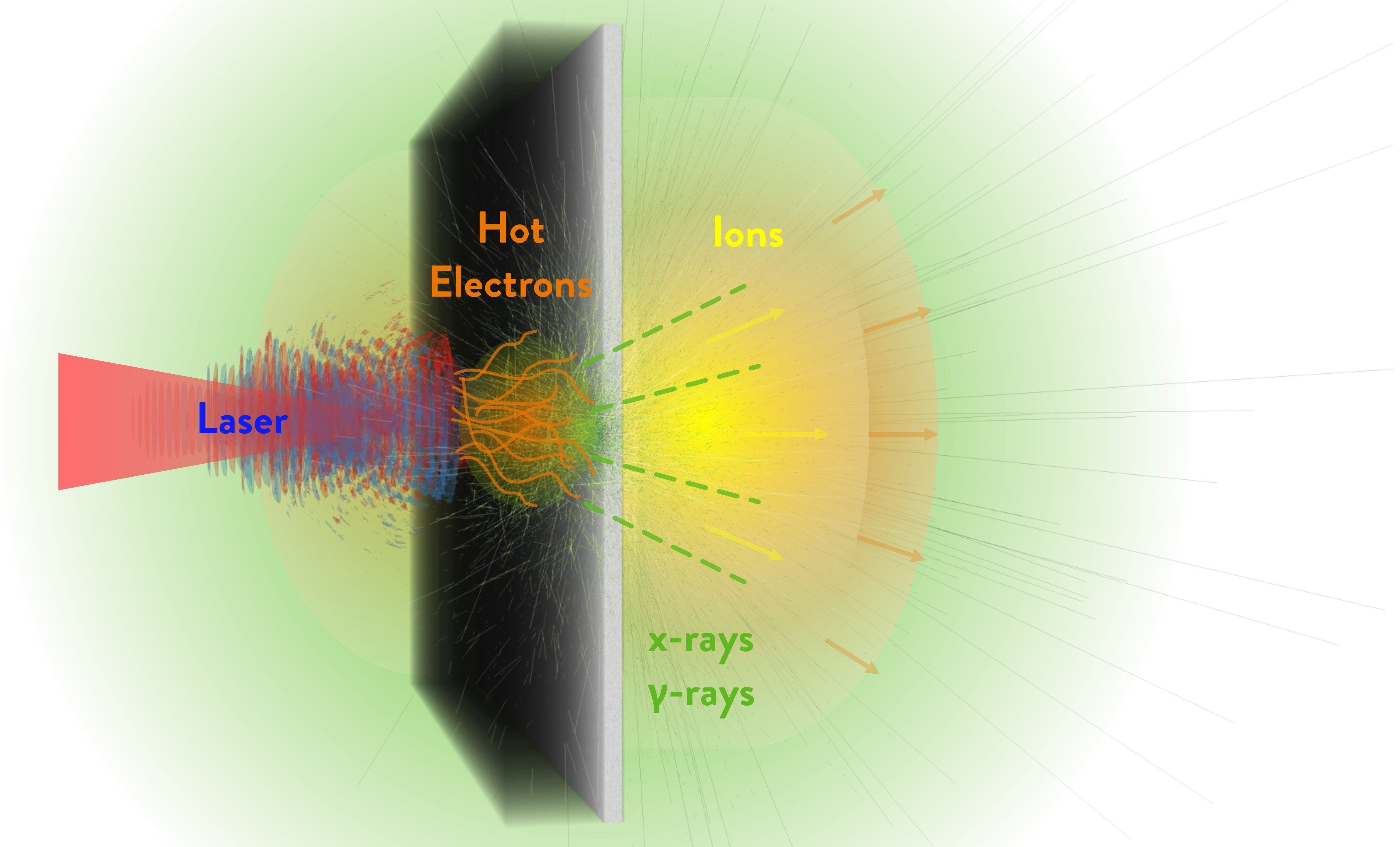
Carbon Foam on **Aluminum** Substrate



Pulsed Laser Deposition (PLD)

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)



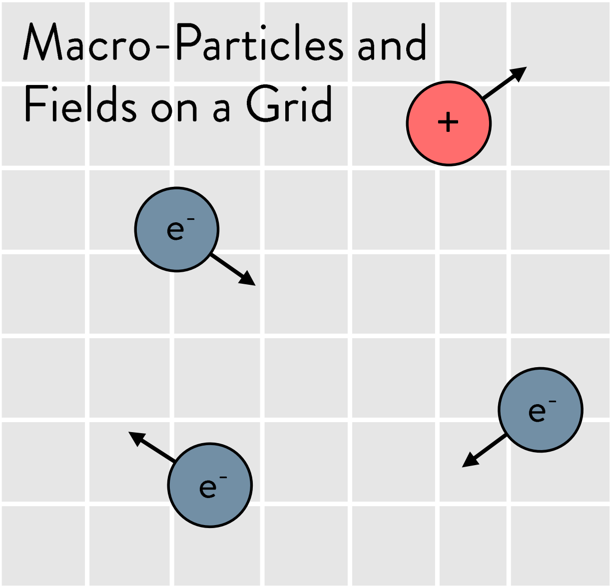
Basic Physics

Plasma Species (electrons, ions, neutrals)

+Electromagnetic Fields

Described by the **Vlasov-Maxwell** system

Approximately solved with **Particle-in-cell** (PIC) simulations

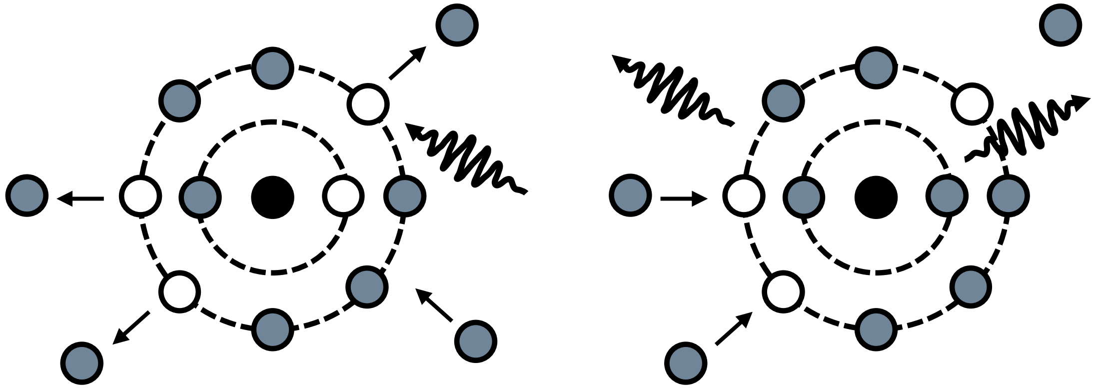


Atomic Processes Physics

Collisional/Field Ionization, Recombination, Excitation, Bremsstrahlung, Disexcitation, Spontaneous Emission, Charge Exchange, Bethe-Heitler Pair Production, ...

Driven by atom/ion collisions with electrons, atoms, ions and photons

Evaluated analytically or simulated with Monte Carlo methods



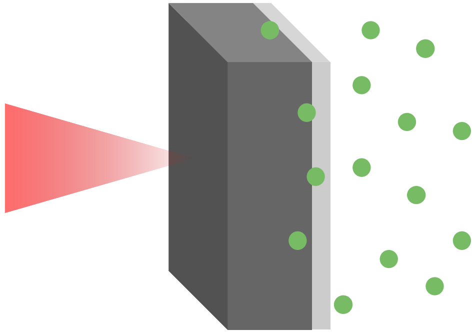
Very challenging to consider all of them!

Continuous High-Energy Photon Emission

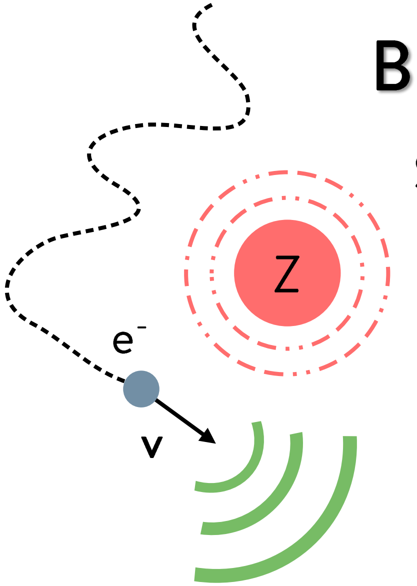
Enhanced Acceleration of Electrons in Foam + Dense Substrate

↓

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



Bremsstrahlung



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

Several cross-sections available:

- Seltzer-Berger (tabulated)
- Bethe-Heitler (analytic)...

Koch, H. W. & Motz, J. W. (1959). Bremsstrahlung Cross-Section Formulas and Related Data. Rev. Mod. Phys., 31, 920–955.

Synchrotron-like Emission (Non-linear Inverse Compton Scattering)

Scattering in the electromagnetic fields and head-on collision with the reflected laser pulse

Motivations of Research on High-Energy Photon Emission

Interests

Complete Description of Laser-Plasma Interaction

Tunable Laser-Driven High-Energy Photon Sources

Applications: Radiography, Tomography, Interrogation of Materials, Diagnostic for laser-plasma

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

Challenges

- Inclusion of all the **relevant physics**
- Choice of **modelling and simulation** strategies
- Limited **computational resources**
- Novelty of **non-conventional targets**

Methods: Monte Carlo inside Particle-In-Cell (PIC)

Evaluation of High-Energy Photon Emission and Radiation Reaction at PIC simulation run-time

- Time interval between two emission events: non-homogeneous exponential distribution with a time-dependent **Rate of Photon Emission**

$$p(t) = \lambda(t)e^{-\tau(t)} \qquad \lambda(t) = dN/dt \qquad \tau(t) = \int_0^t \lambda(t')dt'$$

Bremsstrahlung

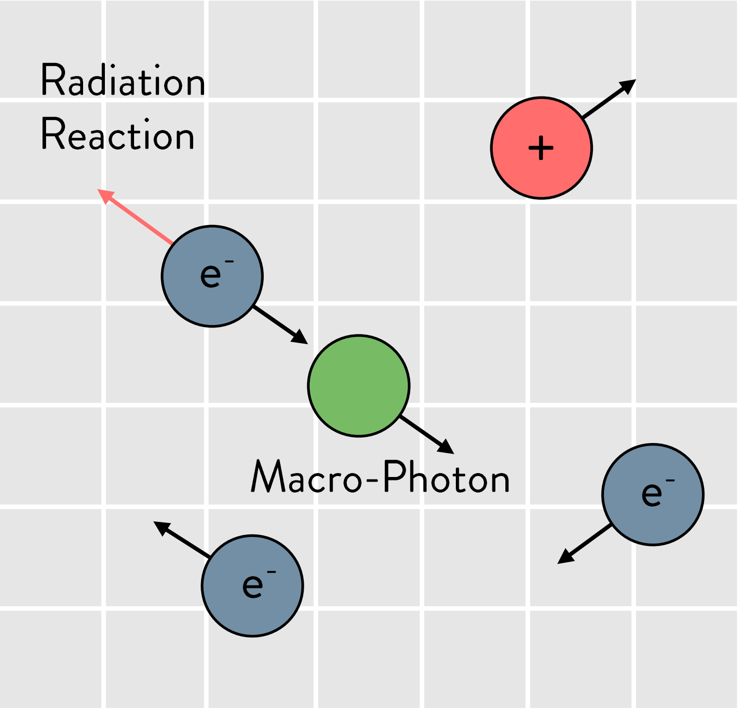
$$\frac{dN}{dt} = n_i \sigma v$$

Synchrotron-like emission

$$\frac{dN}{dt} = \frac{\sqrt{3}}{2\pi}\frac{e^2 m_e c}{\hbar^2}\frac{\chi}{\gamma}\int_0^{+\infty}\frac{F(\omega,\chi)}{\omega}d\omega$$

- Sampling of **Photon Energy** and **Back-Reaction**

$$\mathbf{p}_{ph} = \frac{\hbar\omega}{pc}\mathbf{p} \qquad \mathbf{p}^f = \left(1 - \frac{\hbar\omega}{pc}\right)\mathbf{p}$$



Computational Challenges in PIC:

- ps duration
- thick (1-10 mm) targets
- solid densities (100-1000 n_c)

Required resources

Al Ti Ta W Au

Methods: Monte Carlo inside PIC code EPOCH

EPOCH

Arber, T. D., et al., (2015). Contemporary particle-in-cell approach to laser-plasma modelling. Plasma Phys. Control., 57(11), 113001.

Seltzer-Berger tabulated cross-sections

Seltzer, S. M., & Berger, M. J. (1986). Bremsstrahlung energy spectra from electrons with kinetic energy 1 keV–10 GeV incident on screened nuclei and orbital electrons of neutral atoms with Z = 1–100. Atomic Data and Nuclear Data Tables, 35(3), 345–418.

- from theoretical and experimental results
- range of electron energies: from $m_e c^2$ up to 10 GeV
- atomic screening
- electron-electron bremsstrahlung

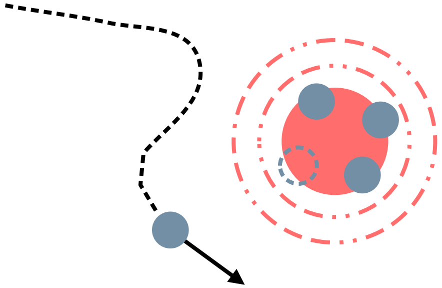
- **Self-consistent** treatment of particle dynamics
- **Mean-Field Approach** to Bremsstrahlung simulation

$$\frac{dN}{dt} = n_i \sigma v$$

- **No collisions** among electrons and ions → collisional approach not available in open-source codes!

Martinez, B., Lobet, M., Duclous, R., d'Humières, E., & Gremillet, L. (2019). High-energy radiation and pair production by Coulomb processes in particle-in-cell simulations. Phys. Plasmas, 26(10), 103109.

- **Screening Effects** not taken into account properly

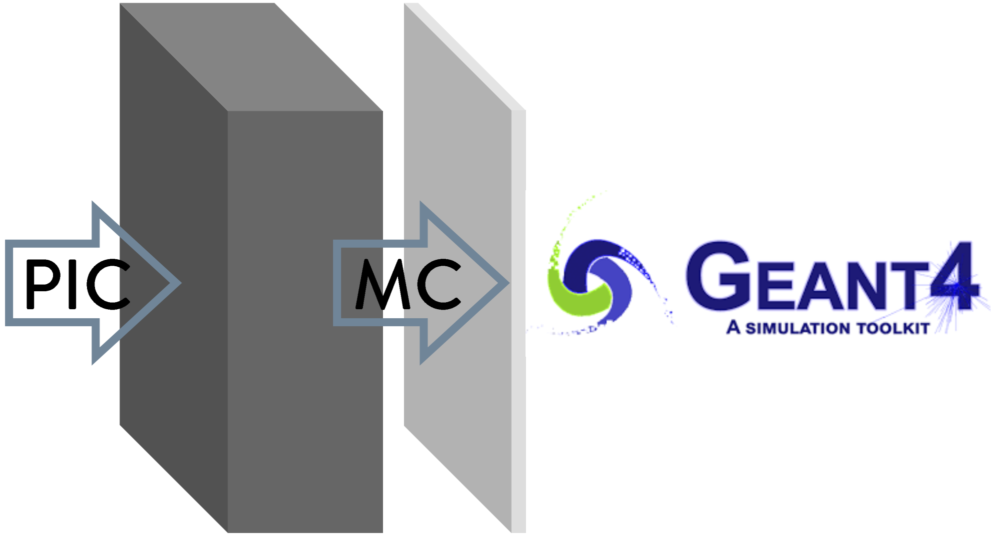


Ionized Species in the Plasma

Methods: Alternatives

Evaluation of High-Energy Photon Emission after PIC simulation

- Feed a **standard Monte Carlo** code with the electron distribution computed by the PIC.



- Standard mean-field approach
- Ignores plasma environment
- Neglects electron dynamics (recirculation)
- Need to think about PIC coupling
- Thick targets → Yes!

- **Analytical estimates**

Bremsstrahlung in DLTs

Simulation Parameters:

- Laser: a_0=20 (8.7x10^{20} W/cm^2), waist 3 μm, FWHM=30 fs
- Carbon foam, densities 2-**5**-10 **n$_c$**, lengths 2-**5**-10-15-20 **μm**
- Minimum Photon energy = 10 keV
- Substrate of **1 μm of Al** → 2D 450 n_c - 3D 80 n_c

Not optimal for Bremsstrahlung

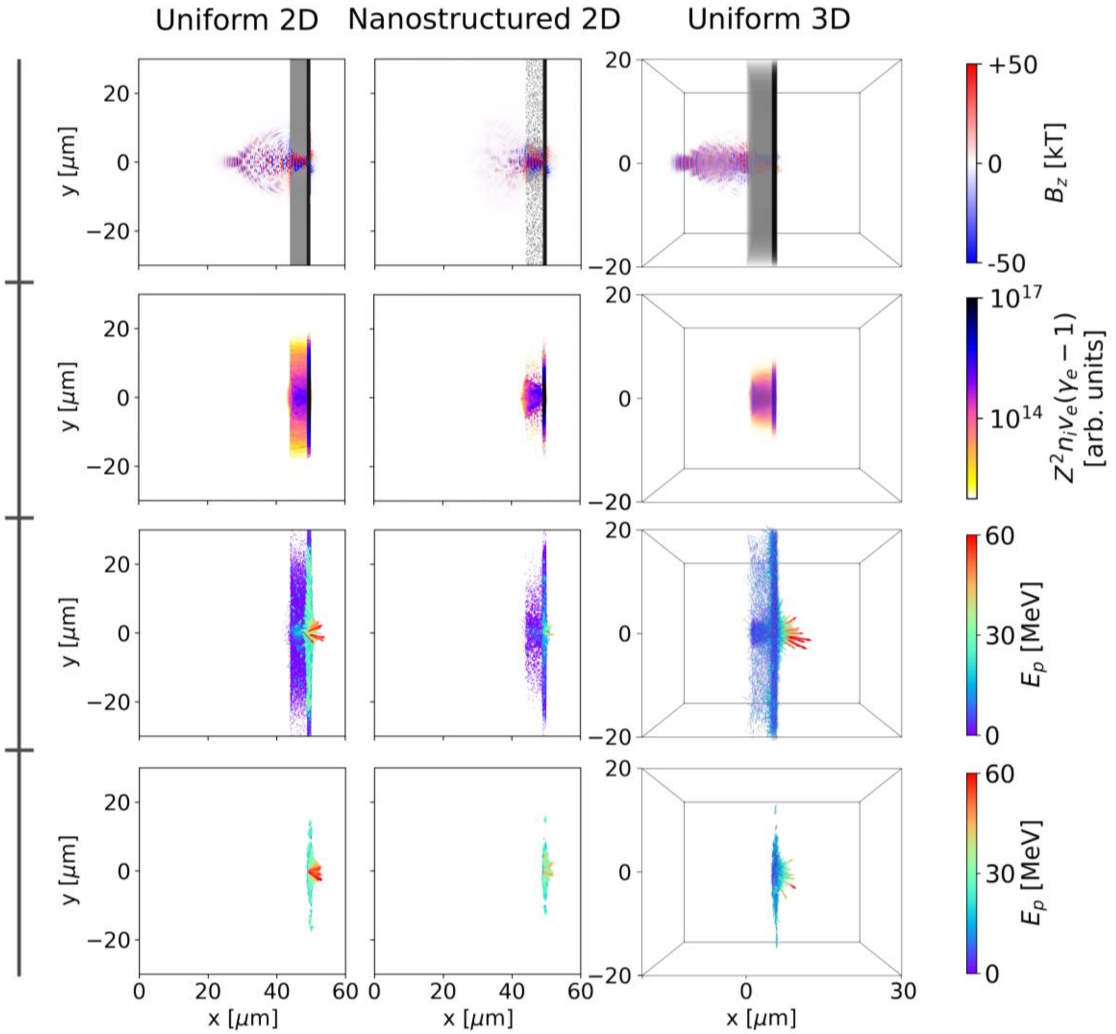
Formenti, A., Galbiati, M., & Passoni, M. (2022). Modeling and simulations of ultra-intense laser-driven bremsstrahlung with double-layer targets. Plasma Phys. Control. Fusion, 64(4), 044009.

Foam Thickness 5 μm - Foam Density 5 n_c

Proportional to the emitted power

Photons as arrows from EPOCH (PIC)

Photon as arrows from GEANT4 (MC)



Analytical estimates for Bremsstrahlung

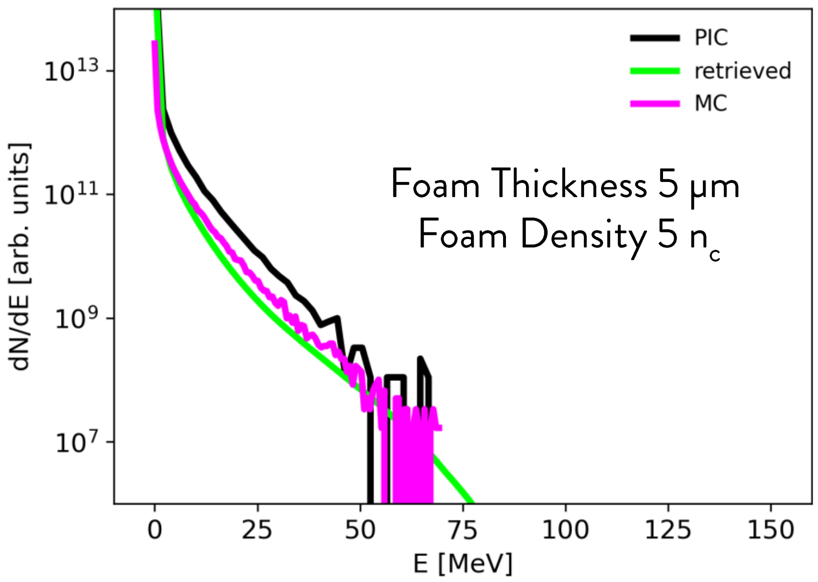
- **Spectrum in energy** of all emitted photons

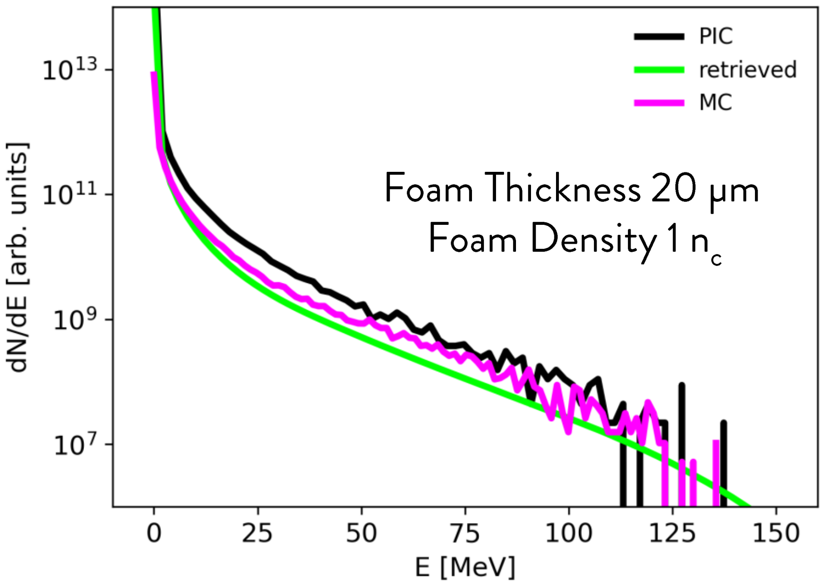
$$\frac{dN_p}{dE_p} = (n_i t)_{sub} \int_{E_p}^{E_{e,max}} \frac{d\sigma}{dE_p} \frac{dN_e}{dE_e} dE_e$$

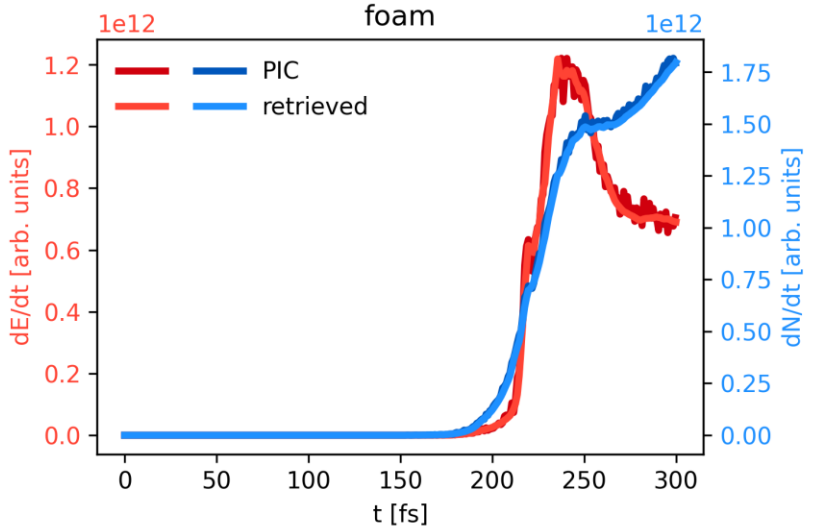
- **Number and Power in emitted photons** by foam and substrate electrons

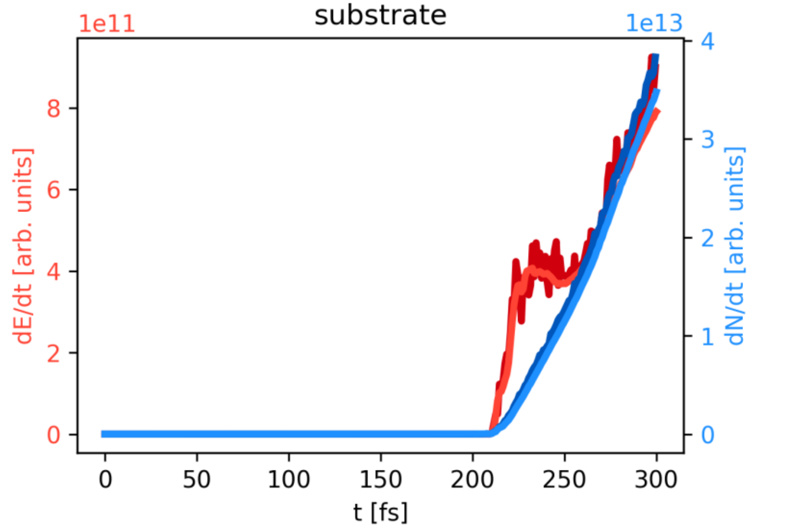
$$\frac{dE}{dt} = \sum_e n_i v_e w_e \int_{E_{p,min}}^{E_e} E_p \frac{d\sigma}{dE_p} dE_p$$

$$\frac{dN}{dt} = \sum_e n_i v_e w_e \int_{E_{p,min}}^{E_e} \frac{d\sigma}{dE_p} dE_p$$

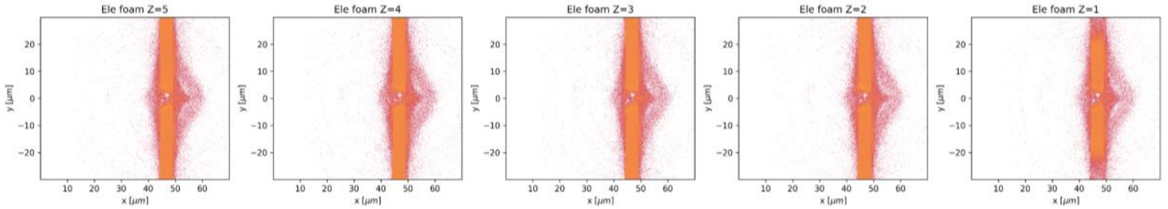




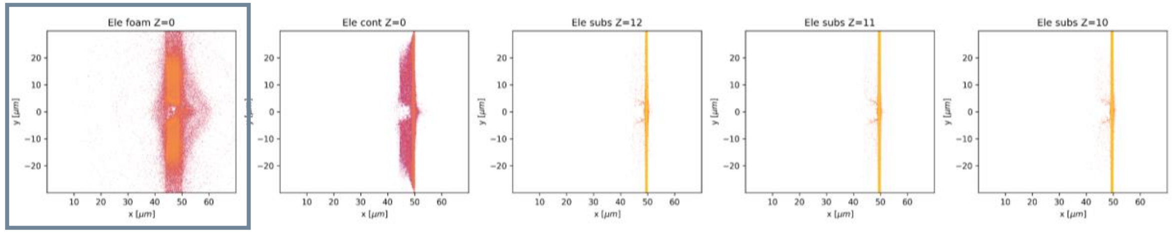




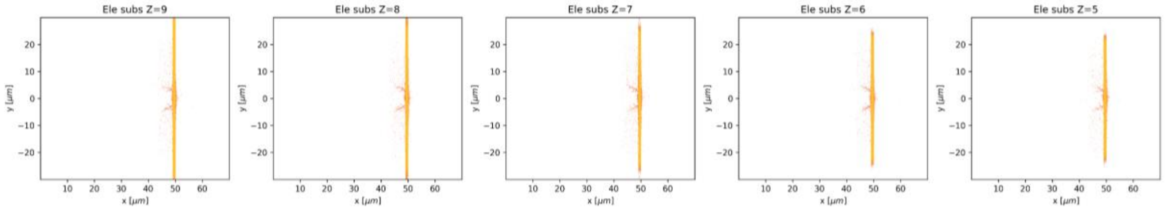
Bremsstrahlung and Field Ionization



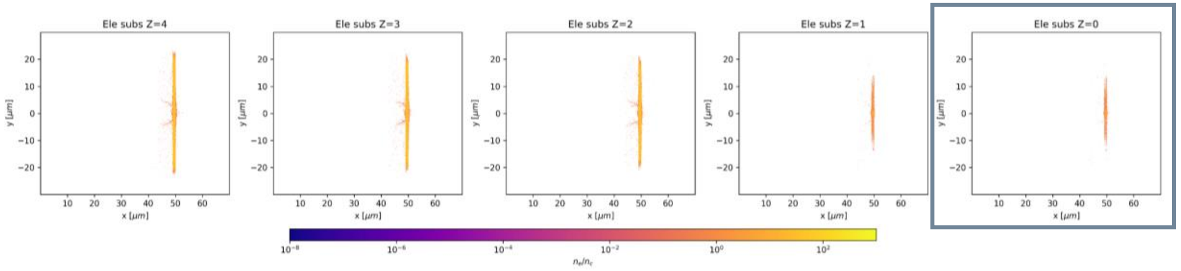
Foam e⁻ from full ionization



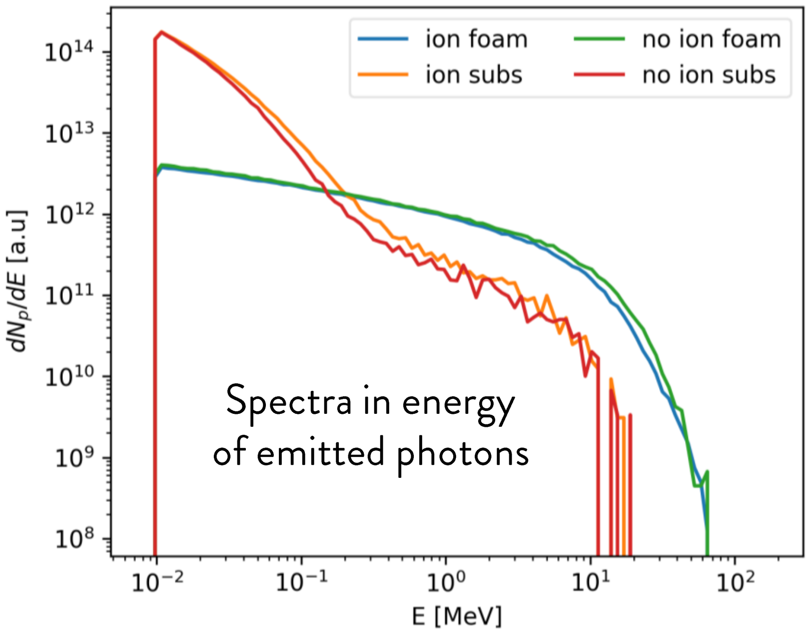
Foam Thickness 5 μm - Foam Density 5 n_c



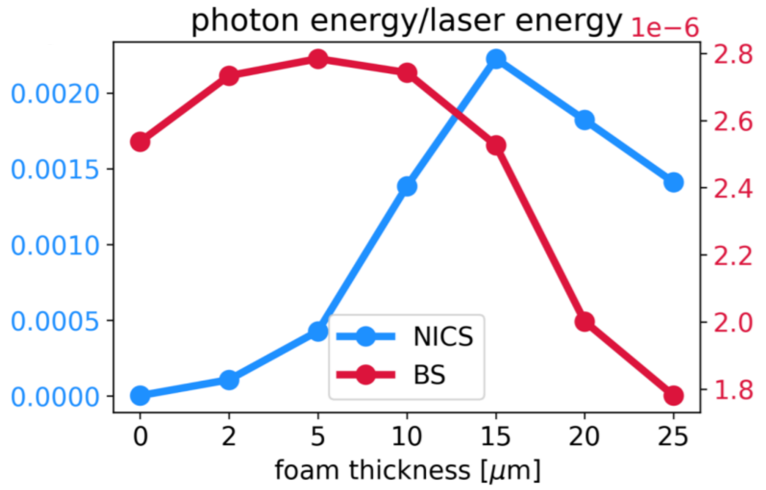
Subs e⁻ from full ionization

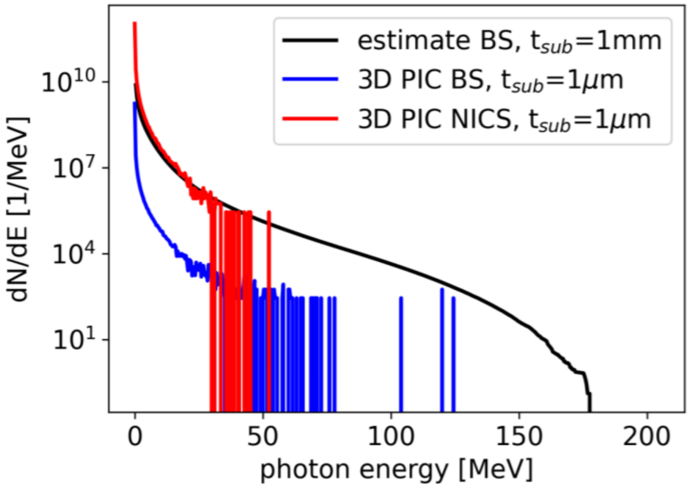


- Posthumus et al. (1997). Molecular dissociative ionisation using a classical over-the-barrier approach. IOP Conference, 154, 298-307.
- Delone, N. B., & Krainov, V. P. (2000). Multiphoton Processes in Atoms.
- Ammosov, M. V., Delone, N. B., & Krainov, V. P. (1986). Tunnel Ionization Of Complex Atoms And Atomic Ions In Electromagnetic Field.



Bremsstrahlung vs Synchrotron-like emission (NICS)

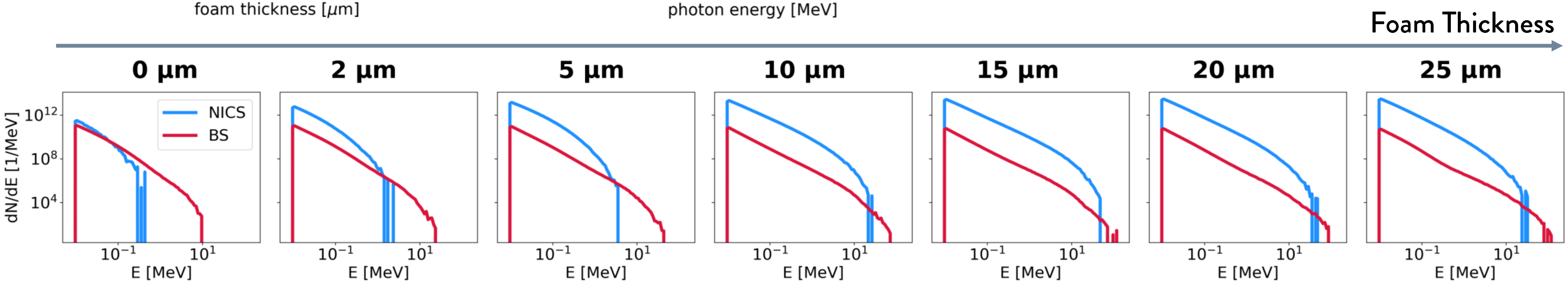




3D Simulations with DLTs

Laser Intensity = 8.65×10^{20} W/cm^2 , a_0 = 20
Aluminium Layer Density = 80 n_c
Aluminium Layer Thickness = 1 μm
Carbon Foam Density = 1 n_c
Foam Thickness = 0-5-10-15-20-25 μm

With **WarpX** and ***EPOCH***



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.

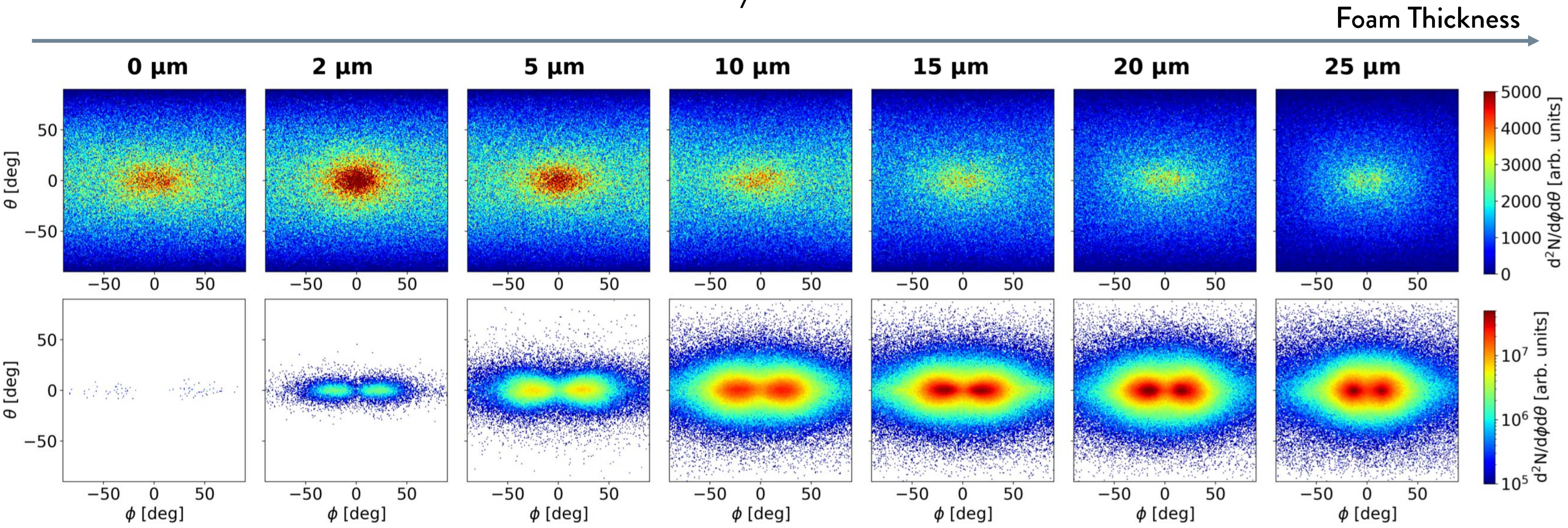
Vay, J.-L., et al.(2021). Modeling of a chain of three plasma accelerator stages with the WarpX electromagnetic PIC code on GPUs. Phys. Plasmas, 28(2), 023105.

Bremsstrahlung vs Synchrotron-like emission (NICS)

Angular Distribution of Photons

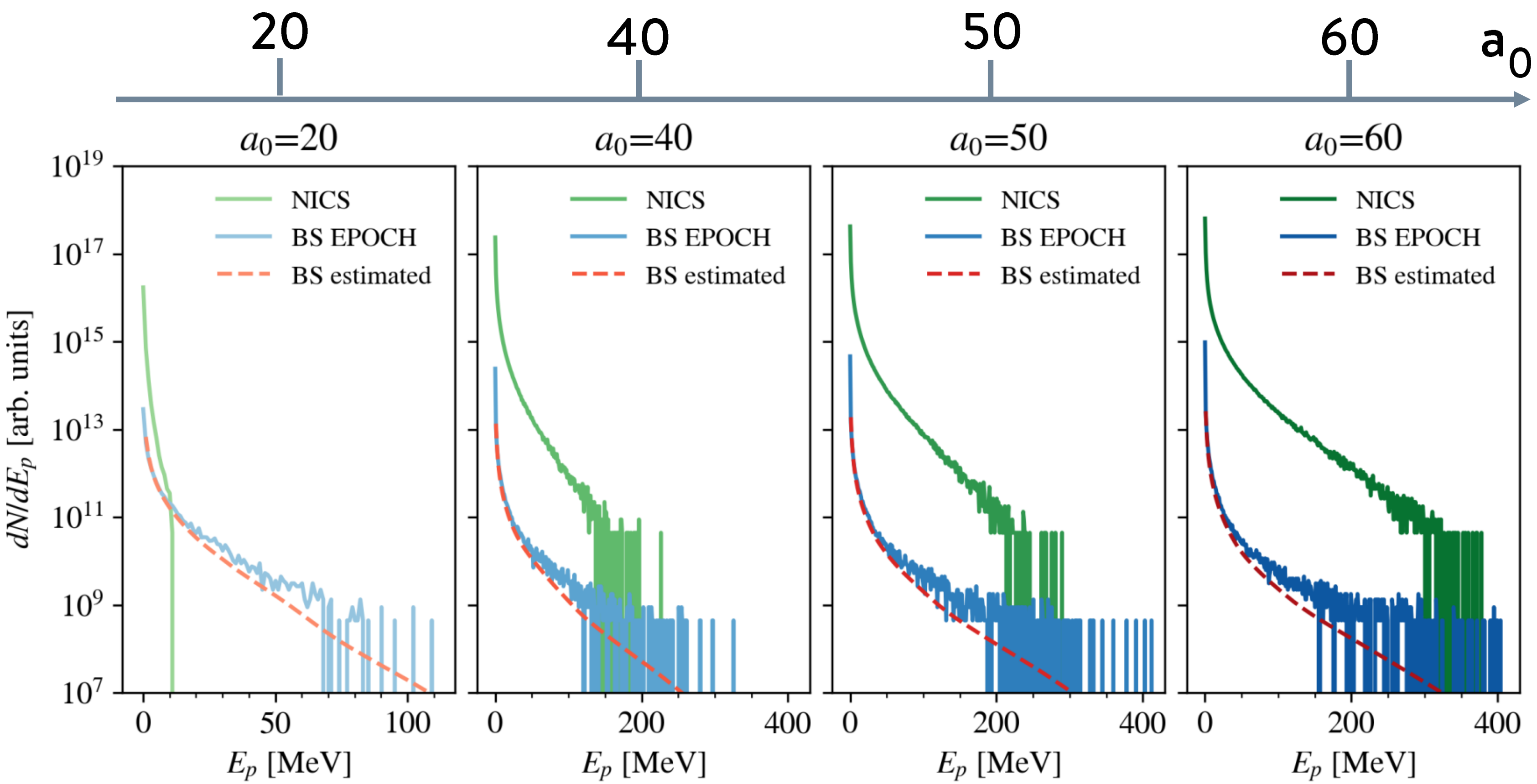
First Row → Bremsstrahlung

Second Row → Synchrotron-like emission



Bremsstrahlung vs Synchrotron-like emission (NICS)

Spectra in energy of all emitted Photons by Electrons



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 n_c

Foam Thickness = 25 μm

With Smilei and EPOCH

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

a= $11\cdot10^{-31}$ m^2

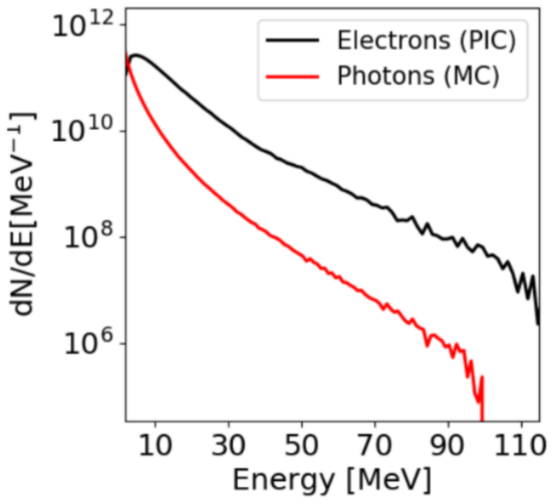
b=0.83

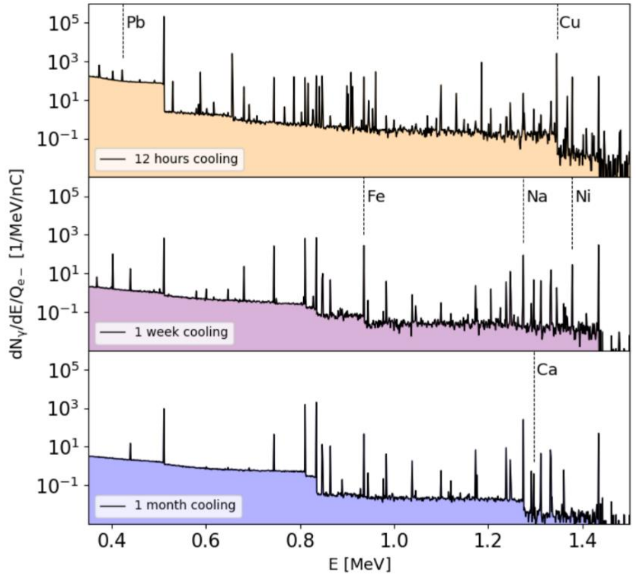
Galbiati, M., Formenti, A., Grech, M., & Passoni, M. (2023). Numerical investigation of non-linear inverse Compton scattering in double-layer targets. Front. Phys., 11.

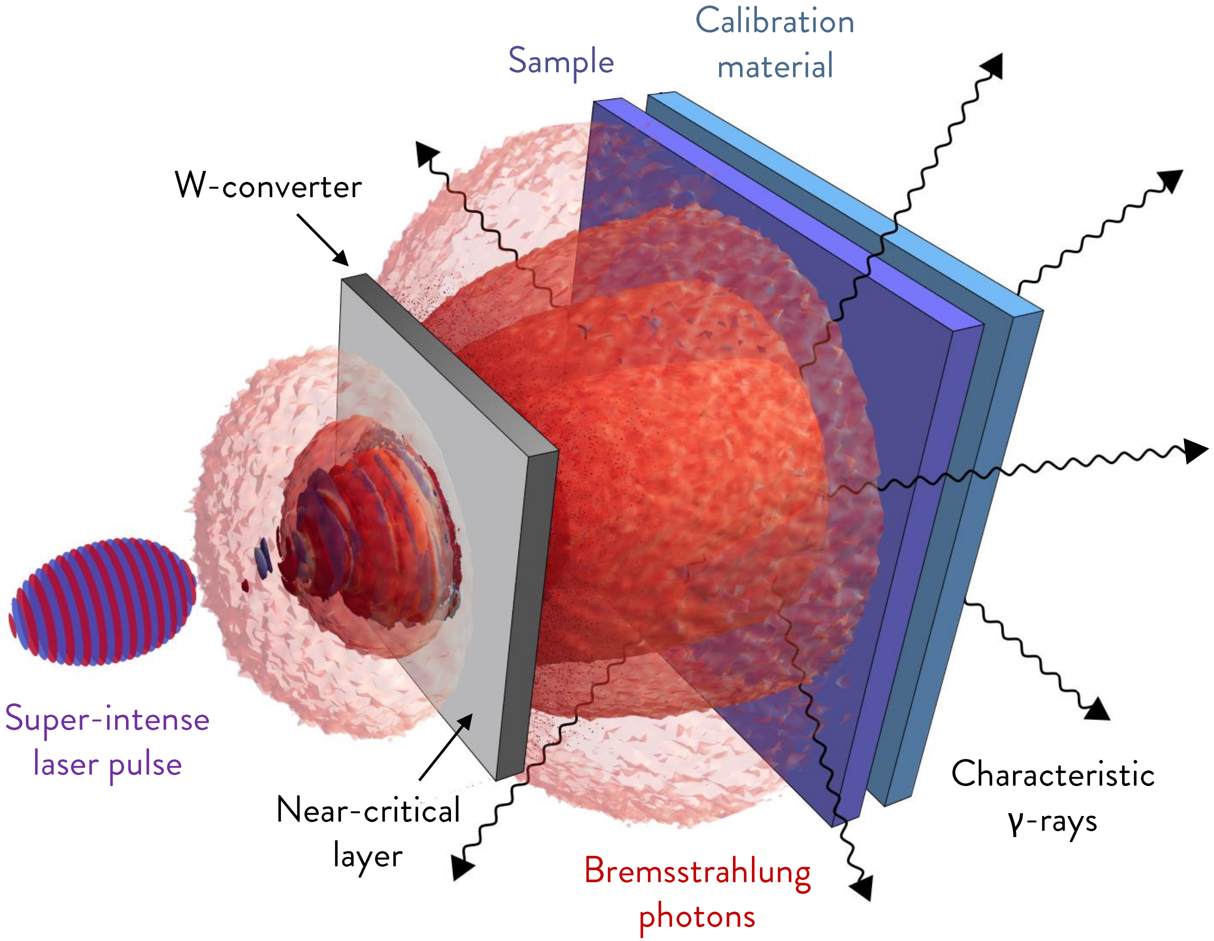
Derouillat, J. et al. (2018). Smilei : A collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation. Comput. Phys. Commun., 222, 351–373.

Photon-Activation Analysis

- Laser interaction with near-critical material (3D PIC) 8×10^{20} W/cm^2
- Hot electrons passing through 2.6 mm W → Bremsstrahlung photons generation (MC:Fluka)
- Sample and comparative material irradiation → Delayed emission of characteristic γ-rays (MC:Fluka)
- Retrieve the elemental composition of a cm-thick homogeneous sample







Mirani, F., Calzolari, D., Formenti, A., & Passoni, M. (2021). Superintense laser-driven photon activation analysis. Commun. Phys., 4, 1.

Laser-Driven Tomography

3D imaging by sections using laser-driven x-rays from a compact laser source.

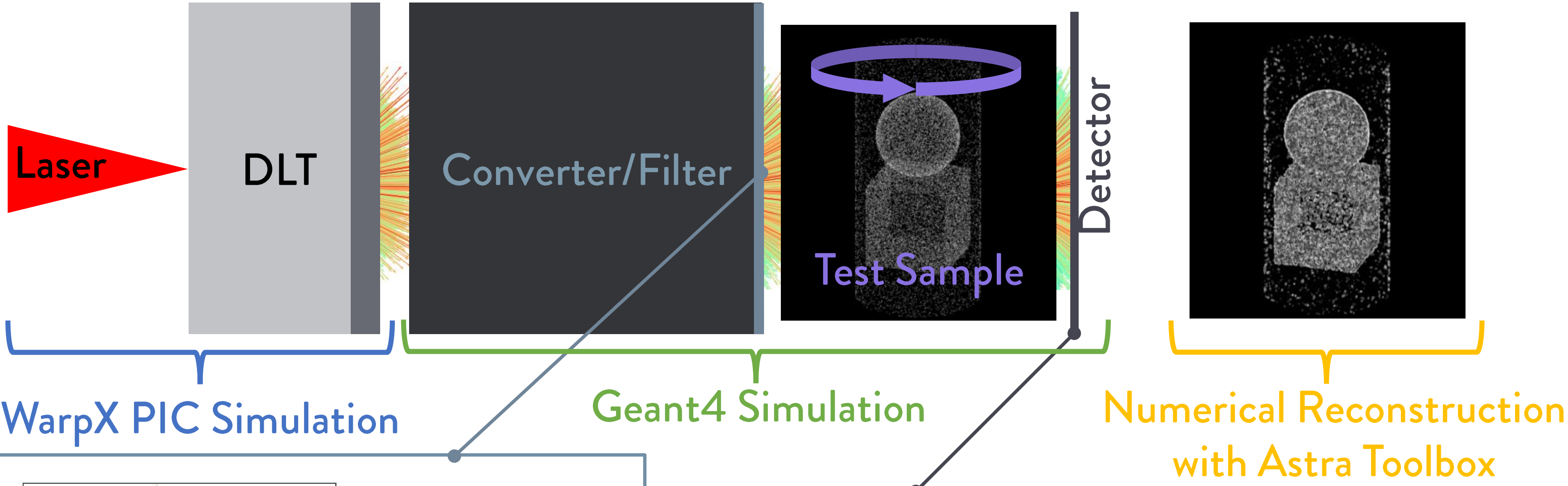
Compact Laser and Optimized Setup

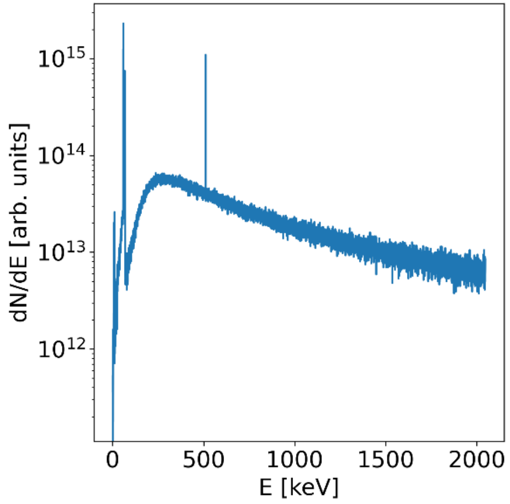
$a_0 = 10$

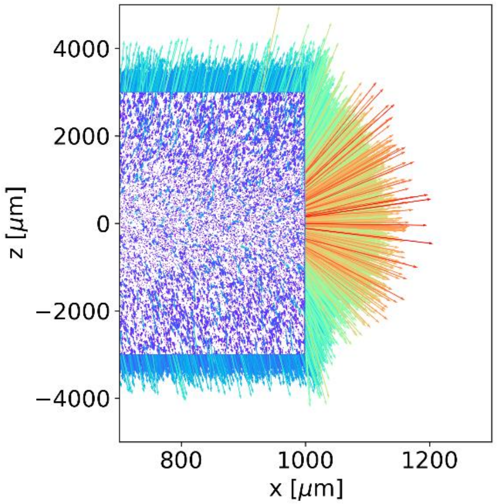
Foam Density = $2\ n_c$

Foam Thickness = 16 μm

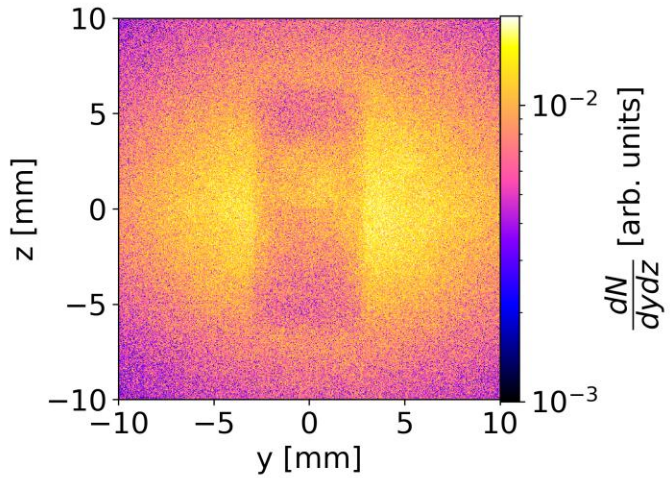
Converter = Tungsten 1mm







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



Radiography of the Test Sample made of Pb, Fe, and W

Conclusions

Bremsstrahlung is a **relevant process in laser-plasma interaction** and is interesting for **tunable laser-driven high-energy photon sources**

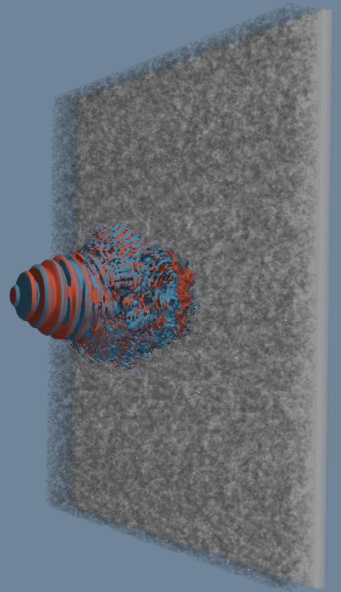
- DLTs can be **optimized** for emission changing target parameters.
- **Complementary modelling strategies** for bremsstrahlung with advantages and disadvantages.

Perspectives

- Investigation of bremsstrahlung in very compact lasers
- Improve bremsstrahlung simulation in PIC
- Include other atomic processes (emission of characteristic x-rays)
- We have planned experiments!

21st meeting on Atomic Processes in Plasmas

15-19 May 2023 - Vienna



Thank you for your attention!

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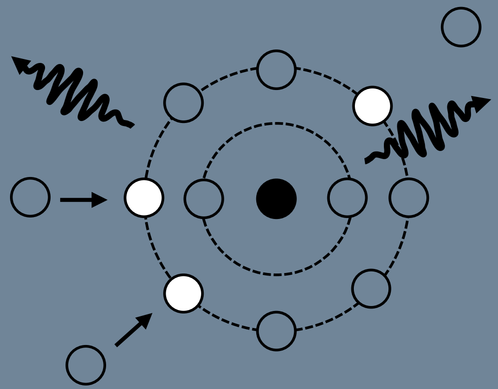

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