

# Numerical Study of the impact of laser irradiation parameters on X-ray Conversion of different materials

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Irradiating a target with a laser leads to the formation of a plasma which absorbs an energy  $E_{abs}$  from the laser incident energy  $E_{inc}$ . In this situation, the absorption ratio's expression is  $\eta_{abs} = E_{abs}/E_{inc}$ . Then, the plasma re-emits a part of the absorbed energy as X-ray radiations ( $E_X$ ). The re-emission ratio is defined as  $\eta_{X,abs} = E_X/E_{abs}$ . Hence, one can deduce an expression of the conversion ratio of the incident laser energy to X-ray emissions:

$$\eta_X = \frac{E_X}{E_{inc}} = \eta_{abs} \times \eta_{X,abs} \quad (1)$$

The conversion has been extensively studied in the 1970's and 1980's. An empirical scaling law has been deduced for the X conversion ratio [1]:

$$\eta_X = 7.5 \times 10^{-2} \times Z \lambda_L^{-0.6} \tau_L^{0.36} \frac{1}{I_0^\alpha + I_0^{-\alpha}} \quad (2)$$

with  $I_0 = \frac{\Phi_L \lambda_L^2}{5 \times 10^{13}}$ ,  $\alpha = 0.55 \lambda_L^{0.7}$  and where  $Z$  is the target material atomic number,  $\lambda_L$  the wavelength of the laser in  $\mu m$ ,  $\tau_L$  the pulse duration in ps and  $\Phi_L$  the laser flux in  $W/cm^2$ .

## Numerical study of the X-ray conversion

A set of 1D and 2D axisymmetric simulations with a limited free-streaming flux (with a flux limiter  $f = 10\%$ ) has been performed with the radiative-hydrodynamic code TROLL aiming at simulating laser-irradiation of plane targets with a square pulse.

Scans of the laser irradiation conditions and target material have been performed leading to a database of 208 1D simulations and 45 2D simulations (see Table 1).

The observables extracted from the simulations are the absorption ratio  $\eta_{abs}$ , re-emission ratio  $\eta_{X,abs}$ , X-ray conversion ratio  $\eta_X$  and the time-integrated X spectra.

## Impact of $\lambda_L$ , $\Phi_L$ & $Z$ on the conversion ratios

Clear dependencies can be drawn from the simulation results. The bell-shaped behavior predicted by the empirical scaling law (2) is exclusively observed for gold (Au) targets. Notably, the simulation results yield X-ray conversion efficiencies that exceed those predicted by the scaling law. Qualitatively, the simulations demonstrate consistent agreement with the dependencies on atomic number ( $Z$ ) and laser wavelength ( $\lambda_L$ ). Across all target materials investigated, the

Table 1: Laser irradiation parameters and target materials used in the simulations

|                                     | DATABASE 1                 | DATABASE 2               |
|-------------------------------------|----------------------------|--------------------------|
| Dimension number                    | 2D                         | 1D                       |
| $\lambda_L$ [ $\mu m$ ]             | 1.06, 0.53, 0.351          | 1.06, 0.53, 0.351, 0.265 |
| $\Phi_L \lambda_L^2 10^{14} W/cm^2$ | 0.01, 0.1, 0.5, 1, 10      | [0.001 -100]             |
| $\tau_L$ [ns]                       | 0.6                        | 0.25, 0.5, 1, 3          |
| $\theta$ [ $^\circ$ ]               | 0                          | 0                        |
| Material (Z)                        | Au (79), Al (13), CH2(4.7) | Au (79)                  |
| Simulations                         | 45                         | 208                      |

absorption ratio exhibits a clear functional dependence on the product of laser flux ( $\Phi_L$ ) and the fifth power of laser wavelength ( $\lambda_L^5$ ). The re-emission ratio shows a positive correlation with atomic number (Z), directly influencing the magnitude of the X-ray conversion ratio. Conversely, this parameter exhibits only a weak sensitivity to variations in laser wavelength ( $\lambda_L$ ).

### Finger prints of the physical models

Considering the classical result of a self-similar ablated plasma leading to  $\eta_{abs} = 1 - \exp^{-K}$  with  $K \sim \frac{v_e L}{c} \sim \frac{\tau_L}{\lambda_L^2 T_e}$  and a heat flux balance at the critical surface  $\eta_{abs} \Phi_L = f n_c T_e v_{th,e} \sim f T_e^2 / \lambda_L^2$ , it is predicted that  $\eta_{abs}$  depends on  $\Phi_L \lambda_L^5$  [2]. The following scaling law can be used to fit the simulation data :

$$\eta_{abs}[\%] = 100 \times \left[ 1 - \exp \left( -3.35 \left( \frac{\Phi_L \lambda_L^5}{10^{12} W.cm^{-2} . \mu m^5} \right)^{-0.43} Z^{0.16} \tau_L^{0.6} [ns] \right) \right] \quad (3)$$

X-ray emission spectra exhibit band structures unique to the target material. The position of the bands can be found in [3, 4]. Then, the total emission spectra can be decomposed in contributions of frequency groups containing one single band (see Table 2 and Fig. 2).

Table 2: Frequency group decomposition of the X spectra per material

|                       | Au    |          |        |             | Al    |        | CH2    |        |
|-----------------------|-------|----------|--------|-------------|-------|--------|--------|--------|
| Bands                 | P     | O        | N      | M           | L     | K      | L      | K      |
| Frequency group [keV] | 0-0.2 | 0.2-0.55 | 0.55-2 | 2- $\infty$ | 0-1.5 | 1.5-10 | 0-0.25 | 0.25-6 |
| Marker Fig.3          | x     | +        | ■      | ◆           | x     | +      | x      | +      |

The evolution of the contribution to the re-emission ratio,  $\eta_{X,abs}$ , of each frequency group function of the absorbed laser flux  $\eta_{abs} \Phi_L$  is a consequence of the physical models of absorption

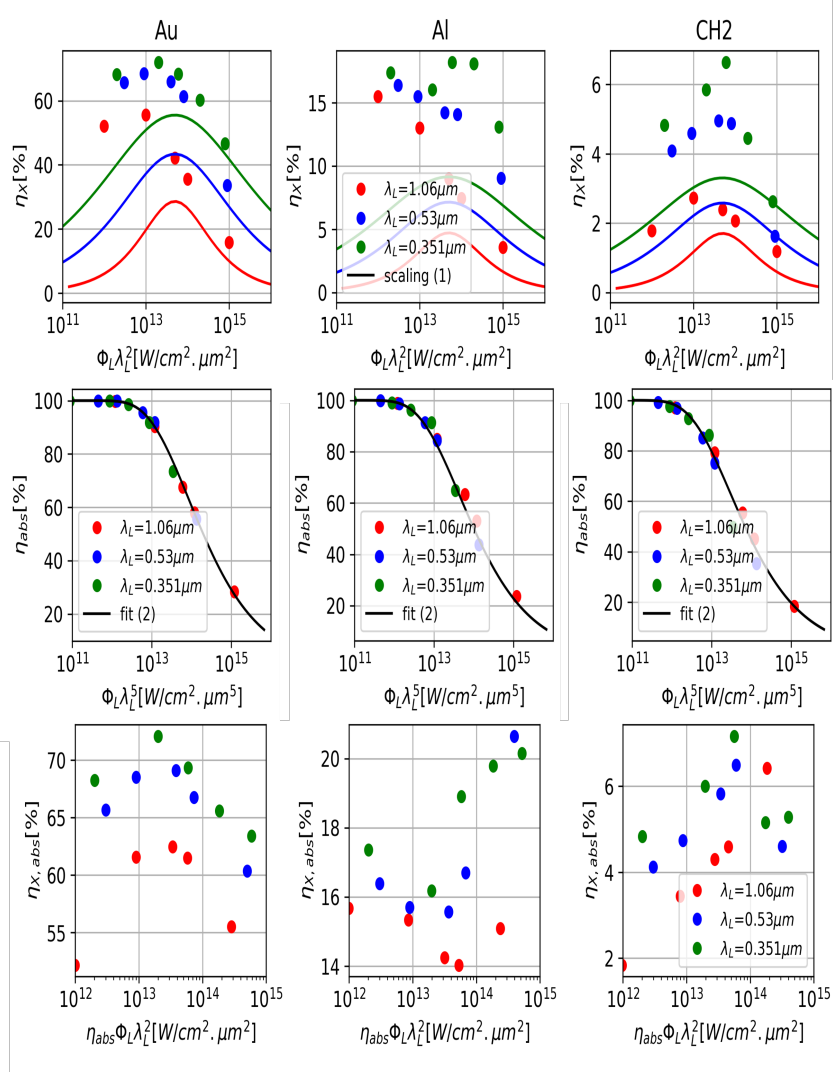


Figure 1: For 3 target materials (left: Au, middle: Al and right: CH2), evolutions of  $\eta_X$  as a function of  $\Phi_L \lambda_L^2$  (top),  $\eta_{abs}$  as a function of  $\Phi_L \lambda_L^5$  (center) and  $\eta_{X,abs}$  as a function of  $\eta_{abs} \Phi_L \lambda_L^2$  (bottom). Data from database 1.

and heat transport.

These contributions to the time integrated spectra can be fitted using a product of an increasing function and a decreasing function such as:

$$\eta_{X,abs} = A \times \frac{1}{1 + \exp\left(\frac{2(\eta_{abs} \Phi_L - x_1)}{\Delta_1}\right)} \frac{1}{1 + \exp\left(\frac{-2(\eta_{abs} \Phi_L - x_2)}{\Delta_2}\right)} \quad (4)$$

The agreement between this fitting formula and the simulations from database 2 is illustrated in figure 4.

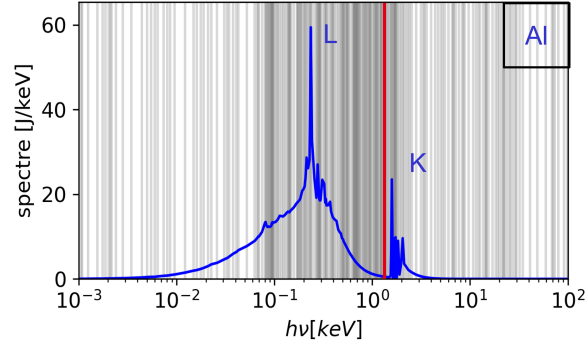


Figure 2: Decomposition of the X-ray emission spectra into frequency groups for Al.

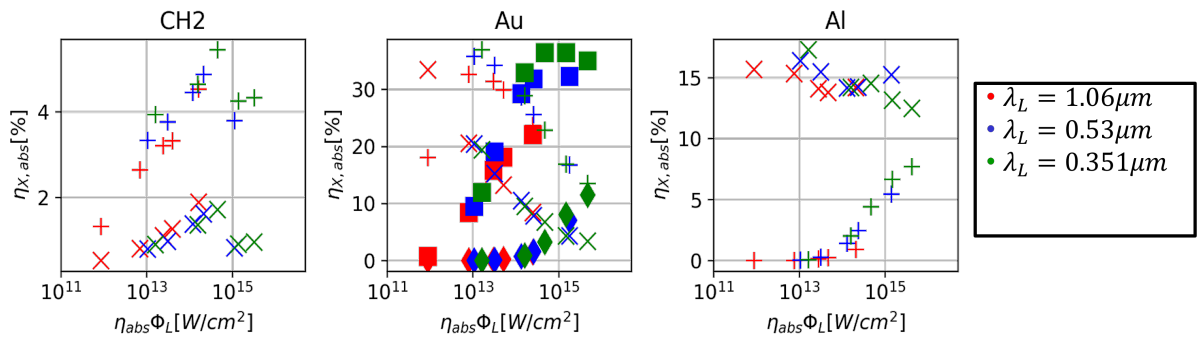


Figure 3: Evolution of the frequency group contributions to the re-emission ratio  $\eta_{X,abs}$  as a function of the absorbed laser flux  $\eta_{abs}\Phi_L$  for 3 target materials: CH2 (left), Au (center) and Al (right). Data from database 1. The marker set is defined in Table 2.

## Conclusions

Simulation predictions of the X-ray conversion ratio are in qualitative agreement with the empirical scaling law but with higher values. It might be explained by the absence of phase plate in the experiments.

Data representation highlights the impact of the irradiation parameters on laser absorption and X-ray emission spectra described by the physical models in TROLL. The metamodels proposed in this contribution can capture these dependencies.

## References

- [1] R. Dautrey, J.P. Watteau, La fusion thermonucléaire inertielle par laser, Part 1, Vol. 2, Chap. IV-II, 1994
- [2] P. Mora, Phys. Of Fluids, 1982
- [3] Mochizuki et al., SPIE Vol 733, 1986

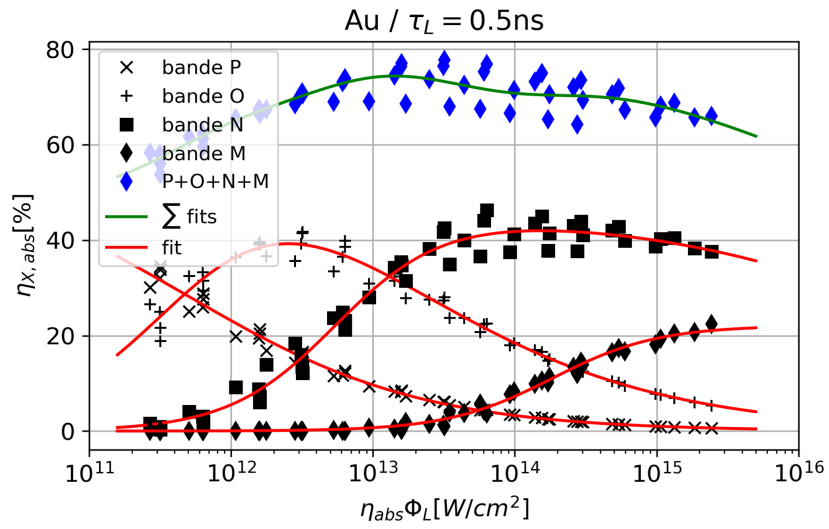


Figure 4: Fit of the frequency group contributions to the re-emission ratio  $\eta_{X,abs}$  using the equation (5).

[4] Mochizuki et al., SPIE Vol 773, 1987