# Measurements and NLTE modeling of mid-Z plasma emission

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## 1 Introduction

The local thermodynamic equilibrium (LTE) approximation is clearly inadequate to model laser mid-Z plasmas where regions of high temperatures and low densities are encountered. LTE cannot be assumed since radiative decay and recombination are not negligible compared to collisional transitions and are not balanced by photo-excitation and photo-ionization. Non-local thermodynamic equilibrium (NLTE) simulations are then extensively used for calculating the evolution of laboratory and astrophysical plasmas and also to simulate spectra for diagnosing the state of these systems. Radiation-hydrodynamics codes require atomic physics routines capable of calculating NLTE quantities such as mean ionization states, specific energies, pressures, opacities and emissivities. For that purpose, the RADIOM [1] model has been designed to provide a rad-hydro code with NLTE data by using LTE tables, at low computational cost. RADIOM has been routinely used for hydrodynamic computations of laser-produced plasmas and substantial improvements have been introduced in the model since the founding paper. Nevertheless, in many experiments involving mid-Z materials we had to face serious difficulties to accurately reproduce with our simulations using RADIOM the measured x-ray yields in the K-shell spectral band and in the soft x-ray band as well [2,3]. Recently, a new NLTE model, NOO-RAD, based on the in-line solution of the NOHEL [4] package, has been incorporated into the FCI2 code. The average ionization obtained from NOHEL is used to calculate an ionization temperature Tz. The NLTE opacities and emissivities are then deduced from the LTE opacities at Tz with the same analytical corrections and source function as in RADIOM. A set of mid-Z materials was experimented at the laser OMEGA facility, by irradiating metallic thin foils of iron (Fe), copper (Cu), zinc (Zn) and germanium (Ge). The x-ray emission of these targets was measured by spectral diagnostics, especially the two broad-band time-resolved spectrometers DMX and micro-DMX from CEA. We report here post-shot simulations of these laser-irradiated foils using RADIOM and NOO-RAD and discuss how the computed x-ray emission compare to the measurements.

## 2 Experimental setup

The targets consisted of 5-μm metallic thin foils held by a Mylar washer of 2-mm inner, 4-

mm outer diameters, and 100-μm thick. The beams were arranged in three cones on each side of the foils: five beams incident at 21° to the foil normal, four beams incident at 42° to the foil normal and ten beams incident at 59° to the foil normal. The beams of the 42° and 59° cones were delayed relative to the beams of the 21°cone by 4 ns, this resulting in power profiles with a pre-pulse prior to a main pulse. The benefit of using pre-pulsed power profiles to increase x-ray emission of thin foils was theoretically and experimentally demonstrated in the context of multi-keV x-ray source generation [5]. The laser-power waveforms driving the targets, as measured during the experiments, are shown in figure 1. The two faces of the foils were each irradiated with ~2.5 kJ during the pre-pulse and ~7 kJ during the main pulse. For each shot, the total backscattered energy was about 2% of the delivered laser energy. A schematic of the experimental arrangement showing the orientation of the laser beams and the main diagnostics is given in figure 2.

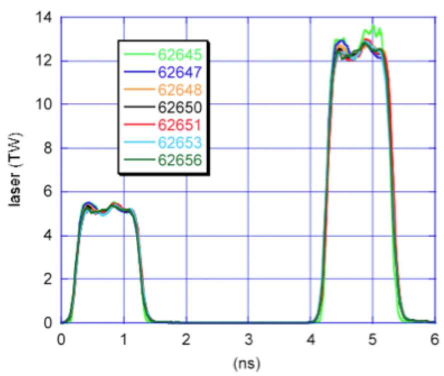


**Fig 1.** Measured laser power pulses

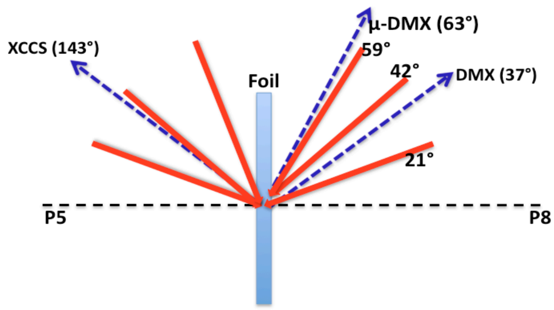


**Fig 2.** Schematic of the experimental arrangement, (beams in red, diagnostics in dashed-blue)

### 3 X-ray emission waveforms and laser-to-x-ray conversion efficiencies

Time histories of x-ray emission in the soft-x-ray spectral bands and the K-shell spectral bands are shown in figure 3 and figure 4, respectively. For each foil, are super-imposed the fluxes as measured with DMX and as calculated with FCI2 during the main laser pulse. Several simulations were performed using a flux-limited Sptizer-Härm formulation and a non-local heat transport model (NLB) [6] for the electron thermal conduction treatment. The flux-limiter $f_e$ was varied between 0.05 and 0.1. In the soft x-ray bands, our simulations over-predict the broad-band x-ray flux for all the foils. The calculated peak fluxes are greater than the measured ones by factors in the range 1.5-1.8, depending on materials and computational models. In addition, the lag between the x-ray and the laser power leading edges is significantly longer for the measured fluxes. For the Fe foil, the discrepancy between the measured and the calculated emitted powers is significantly reduced when NOO-RAD is used instead of RADIOM. A similar visible lowering effect of the soft x-ray powers due to NOO-RAD does not occur for the three other materials. The better agreement with the simulations using NLB is got with a flux-limiter of $f_e = 0.1$. In the K-shell bands, the results are highly dependent on both the materials and the computational models and show a great sensitivity to the electron thermal conductivity model and the associated choice of the flux-limiter. For the Fe, Cu and Zn foils, the simulations using NLB, $f_e = 0.07$ and $f_e = 0.1$, under-predict the broad-band x-ray flux. The simulation results obtained with $f_e = 0.05$ provide in some cases better agreement with the measured emitted powers. For the Ge foil, all the simulations clearly over-predict the emitted power except that using NLB and NOO-RAD that closely match the experimental data. The comparison between x-ray waveforms measured with micro-DMX and calculated with FCI2 leads to similar conclusions.

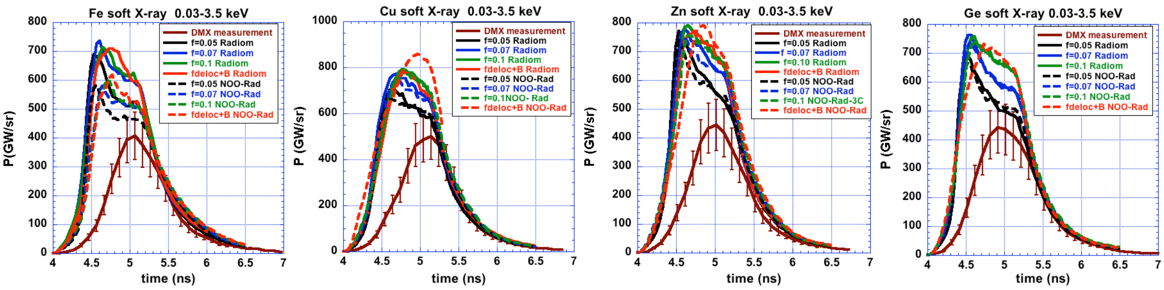


**Fig 3.** X-ray power in 0.03-3.5 keV photon energies emitted in the DMX line of sight, as measured by DMX and as computed by FCI2. The error bars on the measured x-ray powers are ± 20%.

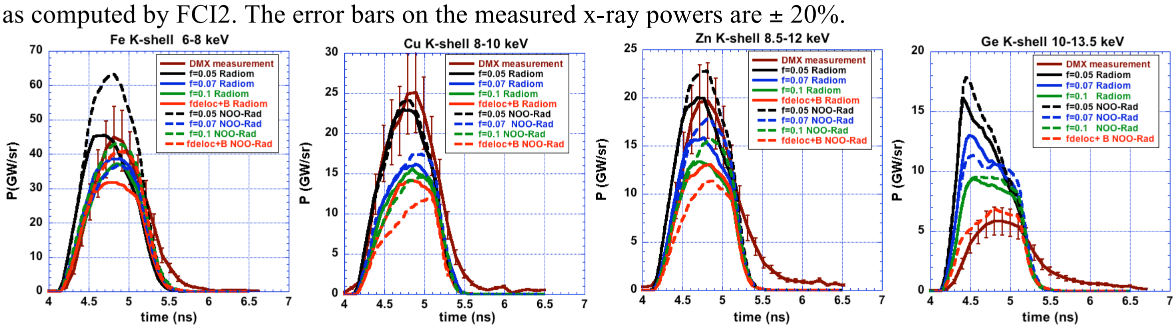


**Fig 4.** X-ray power in K-shell photon energies emitted in the DMX line of sight, as measured by DMX and as computed by FCI2. The error bars on the measured x-ray powers are ± 20%.

The laser-to-x-ray conversion efficiencies (CE) for emission into 4π are given in Table I (soft x-ray bands) and Table II (K-shell bands). For the CE numbers deduced from DMX measurements, the emission anisotropy is estimated with the help of simulations. Consistent with the findings obtained for the x-ray fluxes, the simulations over-predict the energy yields in the soft x-ray band. In the K-shell bands, the measured CEs are greater than calculated for Cu and Zn foils, smaller than calculated for the Ge foil, and are in reasonably good agreement for the Fe foil.

| | DMX data | f = 0.05 RADIOM | f = 0.07 RADIOM | f = 0.1 RADIOM | NLB RADIOM | f = 0.05 NOO-Rad | f = 0.07 NOO-Rad | f = 0.1 NOO-Rad | NLB NOO-Rad |
|---|---|---|---|---|---|---|---|---|---|
| **Fe** | **0.28** | **0.44** | **0.5** | **0.51** | **0.51** | **0.4** | **0.43** | **0.45** | **0.46** |
| **Cu** | **0.34** | **0.47** | **0.55** | **0.57** | **0.56** | **0.48** | **0.53** | **0.56** | **0.64** |
| **Zn** | **0.32** | **0.48** | **0.54** | **0.56** | **0.55** | **0.47** | **0.53** | **0.55** | **0.57** |
| **Ge** | **0.35** | **0.46** | **0.53** | **0.56** | **–** | **0.46** | **0.53** | **0.56** | **0.56** |

**Table I**. Laser-to-x-ray efficiencies into 4π in the 0.03-3.5 keV photon energies, as calculated with FCI2 and as deduced from DMX measurements. The measured CEs are given with a ± 20% uncertainty.

| | DMX data | f = 0.05 RADIOM | f = 0.07 RADIOM | f = 0.1 RADIOM | NLB RADIOM | f = 0.05 NOO-Rad | f = 0.07 NOO-Rad | f = 0.1 NOO-Rad | NLB NOO-Rad |
|---|---|---|---|---|---|---|---|---|---|
| **Fe** | **0.025** | **0.022** | **0.020** | **0.020** | **0.020** | **0.031** | **0.021** | **0.026** | **0.025** |
| **Cu** | **0.015** | **0.011** | **0.009** | **0.0088** | **0.0083** | **0.012** | **0.010** | **0.0088** | **0.0072** |
| **Zn** | **0.012** | **0.010** | **0.0084** | **0.0074** | **0.0077** | **0.011** | **0.0094** | **0.0085** | **0.0064** |
| **Ge** | **0.0045** | **0.0073** | **0.0065** | **0.0055** | **–** | **0.0080** | **0.0067** | **0.0060** | **0.0048** |

**Table II**. Laser-to-x-ray efficiencies into 4π in the K-shell photon energies, as calculated with FCI2 and as deduced from DMX measurements. The measured CEs are given with a ± 20% uncertainty.

## 4 Summary and conclusion

NLTE radiative emission of foils made of mid-Z metallic materials was quantitatively characterized on the Omega laser facility. The broad-band x-ray fluxes measured with DMX and micro-DMX have been compared with results of FCI2 simulations using the NLTE models RADIOM and NOO-RAD. NOO-RAD is designed with the aim of benefiting from both a better calculation of the ionization temperature and the high quality of opacity data given by LTE tables. The principal findings of this work is that NOO-RAD does not provide, for the experiments presented here, significant better agreement with measured x-ray emission data than RADIOM does. The yields in the soft x-ray bands, which account for 90% of the total radiated energy, are still over-predicted by the simulations, even if a slight improvement is obtained for the Fe plasma. These findings confirm the difficulty for NLTE models based on an ionization temperature approach to accurately compute the x-ray emission of under-dense hot mid-Z metallic plasmas.

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