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Enhanced X-ray emission from laser-produced gold plasma by double pulses irradiation of nano-porous targets

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A R T I C L E I N F O

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A B S T R A C T

Enhancement of the soft X-ray emission including free–free, free–bound and bound–bound emissions from Au nano-porous targets irradiated by single and double laser pulses is studied through numerical simulations. Laser pulses of duration 2 ns are used in calculations considering different prepulse intensities and a fixed intensity of 10^{13} W cm^{-2} for the main pulse. The effects of prepulse intensity and time separation between laser pulses are studied for targets of different porosities. Results show that the X-ray yield can be enhanced significantly by a nano-porous target having optimum initial density. Such enhancement can be more improved when double laser pulses with appropriate delay time and intensities irradiate nano-porous targets. It is shown that the enhancement will be reduced when the prepulse intensity is greater than a specific value.

1. Introduction

Laser produced plasmas have been investigated for many years as bright and compact sources of X-rays and have been extensively studied in both long and short pulse regimes [1–4]. X-ray pulses from such sources have been proposed for many potential applications including micro- and nano-lithography [5], high resolution X-ray microscopy [6], inertial confinement fusion (ICF) and material science [7,8]. In practical applications, it is greatly desirable to increase the laser energy absorption and also conversion of absorbed energy into X-rays which depends dramatically on the laser–matter interaction physics and subsequent redistribution of absorbed energy within the material [9]. It has been reported that X-ray yield can be enhanced considerably by using structured targets like gratings, nanoparticle-coated, droplet, metal nanorod arrays, gas puff and porous targets [10–23]. Prepulse technique has also been used to enhance X-ray emission [24,25]. Specially, prepulses have been used to structure the plasma interaction surface so as to enhance surface–wave coupling, to increase the laser absorption [26–28]. It is shown that nano-structured metal targets can enhance X-ray yield in the regime of short laser pulses [29–31]. Some theoretical and experimental works in the field of low density structured materials, such as nano-porous or foam-like targets have shown that such targets can improve the laser absorption leading to enhanced X-ray yield [32–34].

In this paper we study the enhancement of total X-ray emission including free–free, free–bound and bound–bound emissions from nano-porous Au targets irradiated by long laser pulses under different prepulse conditions. The plasma hydrodynamics was simulated by EHYBRID code and the time dependent electron density n_e and temperature T_e of the plasma, were used to calculate the Bremsstrahlung and recombination emissions from the plasma. Bound–bound emissions are calculated using fully time-dependent atomic physics with radiative transfer calculations. A computer code was also developed to calculate the X-ray emission yields and the effects of target porosity and delay time between two irradiating pulses and also prepulse intensity are studied to predict optimum conditions. In a previous work, we reported line X-ray emission from both solid and porous targets under double pulses irradiation in the narrow band lithography region (13.5–13.7 nm) [34]. We showed that in that small spectral range, using a prepulse can reduce the line X-ray emission in the condition of porous target. Also, in some previous works [23,25], we reported the effects of using prepulses in the conditions of solid and porous targets on continuum X-ray emission and because of complexity of calculations, the line emission contribution was ignored in calculating the X-ray yield. However, here we extended those calculations by considering the line emission and absorption which become very important especially for high-Z plasmas like gold plasma.

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2. Methods of calculations

To obtain the total X-ray spectrum, emissivity, η, and opacity, κ, of the plasma as a function of frequency are calculated which are defined as:

$$\eta(\nu,x) = \eta^B(\nu,x) + \eta^R(\nu,x) + \eta^L(\nu,x) \tag{1}$$

$$\kappa(\nu,x) = \kappa_{ff} + \kappa_{bf} + \kappa_{bb} + \kappa_s \tag{2}$$

where, η^B, η^R and η^L are Bremsstrahlung, recombination and line emissivities and κ_{ff}, κ_{bf} and κ_{bb} are free–free, bound–free and bound–bound absorption coefficients, respectively [35–38]. Also, κ_s is the Thomson coefficient which stands for radiation scattering by free electrons. In this study, total X-ray yield including Bremsstrahlung, recombination and line emissions is calculated from laser produced gold plasma. Calculations of the first two mechanisms which result in continuum spectra are presented in our previous works in details [23,25,33]. Here, in addition to the continuum spectrum, the line emissivity and opacity are also calculated to obtain more trustworthy results. The modeling of X-ray line spectra requires fully time-dependent atomic physics and hydrodynamics with radiative transfer calculations.

The emissivity due to a transition from the upper level j to the lower level i can be calculated by:

$$\eta^L(\nu) = \frac{1}{4\pi} N_j h\nu_0 A_{ji}\phi(\nu), \tag{3}$$

where, A_{ji} is the radiative transition probability for the given transition from level j to i, the quantity N_j is the upper state population and ν_0 is the central frequency of the transition. $\phi(\nu)$ is the line profile function which determines the frequency dependence due to Doppler and natural broadening [13] and h is the Planck's constant. We can calculate the absorption coefficient of the same transition by:

$$k_\nu = \left(\frac{\pi e^2}{m_e c}\right)\left[1 - \frac{g_i N_j}{g_j N_i}\right] N_i f_{ij}\phi(\nu), \tag{4}$$

where, N_i is the population of lower level, g_i and g_j are statistical weights of the states, f_{ij} is the oscillator strength of the radiative transition, e and m_e are the electron charge and mass and c is the speed of light. The propagation of radiation through the plasma medium is affected by absorption, emission, and scattering processes which can be considered through the equation of radiative transfer:

$$\frac{dI(\nu,x)}{dx} = -\kappa(\nu,x)I(\nu,x) + \eta(\nu,x), \tag{5}$$

where, $I(\nu,x)$ is the radiation intensity.

The plasma is assumed to be produced by high intensity long laser pulses irradiating the nano-porous target. Laser–target interaction and plasma hydrodynamics are simulated by one-dimensional Lagrangian code EHYBRID [39] which is designated to operate in planar geometry. The code uses a 98 Lagrangian cell matrix in the direction normal to the target surface. The plasma is hence modeled in the direction parallel to the driving laser by cells, which are assumed to be laterally isothermal. EHYBRID code describes many physical processes, including the laser energy deposition, hydrodynamic motion, electronic thermal conduction, ion–electron thermalization coupled with the atomic physics of the plasma ions. In EHYBRID, the time dependent ionization is calculated using a non-LTE collisional radiative (CR) model. The model includes a sophisticated treatment of time dependent atomic physics in plasmas. Collisional excitation, de-excitation, radiative decay, collisional ionization, three-body recombination, radiative and dielectronic recombination processes are included in the coupled rate equation solution as for each level. In this model, population of different ionic levels is calculated by solving the system of rate equations. The rate equations can be solved using direct solution of the system of equations, which may involve thousands of levels or by using a configuration average (CA) approximation. Here, we considered the configuration average model. Fore more details about the non-LTE CR model and the way of solving rate equations please refer to [40,41].

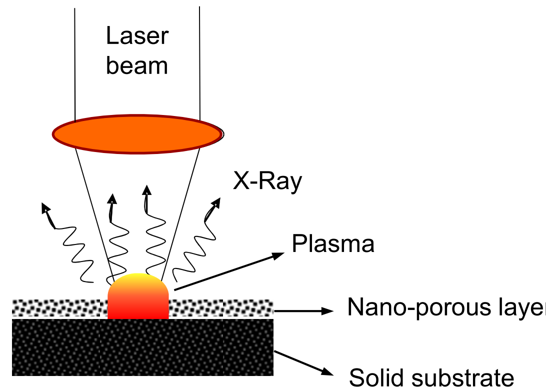

Fig. 1. Porous target including a substrate with solid density covered by a porous nano-layer with lower density.

EHYBRID provides the required plasma parameters like electron density (n_e), electron and ion temperatures (T_e, T_i), average ionization (Z^*) and mass density at each time step for all plasma cells in its output. The results were used as inputs in a post-processor code for detailed calculations of continuum and line emissions. The code can simulate laser ablation process of two-layer targets as well as simple one-layers. Initial parameters for each layer such as initial ionization, temperature, mass density and thickness can be separately specified in the input file.

It was assumed that the nano-porous target (Fig. 1) is consisting of two layers: a gold substrate with solid density ρ_s, and a porous-layer with lower density ρ_n and nano-scale thickness.

The porosity of the nano-layer can be characterized by the ratio of ρ_n/ρ_s. The target thickness was assumed to be 10 μm, including a substrate with thickness 7 μm and a nano-porous layer with thickness 3 μm. In the simulations, typically 70 cells was considered for the nano-layer and the remaining 28 cells for the substrate. Targets are assumed to be irradiated by 2 ns laser pulses of wavelength 1.06 μm and different intensities. By extracting data from EHYBRID output and using relations (1)–(5), total X-ray yield was calculated for various irradiation conditions in soft X-ray wavelength region (0.1–10 nm). This wavelength range selection is due to its importance especially for gold plasma in indirect-drive Inertial Confinement Fusion (ICF) studies where gold layers are mostly used as inner wall of the "hohlraum" [42].

3. Results and discussion

Using the time dependent temperature and density across the target in each specific time (during the irradiation and after), the emitted X-ray yield was calculated for Au nano-porous targets irradiated by 2 ns laser pulse of intensity 10^{13} W cm^{-2}. Fig. 2(a) shows an example of the calculated line spectra for a laser produced Au plasma with average ionization $Z^* = 29$ which is obtained for a plasma cell of temperature 188 eV at the density 4.6×10^{21} cm^{-3} (this is obtained from non-LTE calculations in hydro code). More details about the laser-produced gold plasma parameters such as temperature, density and corresponding charge states can be found in Ref. [33]. These results are obtained considering all possible transitions between bound states of Au^{+29}.