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Enhanced x-ray emissions from low-density high-Z mixture plasmas generated with intense nanosecond laser

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ABSTRACT

Enhancement of x-ray emissions from laser-produced plasmas is imperative for various applications. Low-density Au–Gd mixture was proposed to enhance the x-ray emissions. X-ray emissions were simulated for the laser-irradiated gold and Au–Gd mixtures with different initial densities. It was shown that 1.34 times conversion efficiency has been achieved for the 0.05 g/cm^3 Au–Gd (6/4) mixture comparing with the 10 g/cm^3 gold. The enhancement is attributed to higher Rosseland mean opacities of the mixture and reduction of the ion kinetic energy caused by the lower initial density.

1. Introduction

Investigation of laser-plasma x-ray sources has been one of the primary objectives in plasma physics due to a variety of attractive applications, such as x-ray backlighting [1], advanced lithography [2], and inertial confinement fusion (ICF) [3]. Especially, the x-ray sources from multi-eV to multi-keV emitted from laser-produced high-Z plasmas are essentially required in many experiments, including radiation transport in astrophysics, opacity measurements [4], and plasma property investigating in high energy density physics [5] as well as the indirect-drive ICF research. In all of these applications, it is desirable to enhance the intensity of the laser-plasma x-ray sources.

The x-ray intensity from laser-produced plasmas depends on laser energy and laser to x-ray conversion efficiency. In order to enhance the conversion efficiency, substantial work has been carried out by varying laser parameters such as wavelengths, pulse shape, pulse duration and intensity in various target materials and structures [6,7]. Due to their significantly higher Rosseland mean opacities [8–12], various high-Z mixtures have been proposed to enhance the x-ray emissions [13,14]. In 1992, H. Nishimura et al. validated experimentally for the first time that the absolute x-ray emission from the ns laser-irradiated Au–Sm and Au–Tb mixtures at the optimum mixing ratio had higher conversion efficiencies than their constituent materials [15]. In 2003, J.A. Chakera et al. observed that the soft x-ray emission from laser-irradiated Au–Cu mix-Z targets in the spectral region 15–150 Å is higher than those for individual elements [16]; From the recent study by S. Chaurasia et al. in 2008, a substantial enhancement of x-ray emission in a narrow spectral region of 1.5–3.9 Å was observed from laser plasmas of Au–Cu mixture [17]. On the other hand, low-density targets have also been used to increase the conversion efficiency. T. Okuno et al. demonstrated experimentally that the conversion efficiency of laser to extreme ultraviolet (EUV) emission at 13.5 nm was enhanced significantly by using the low-density Sn target [18]. C.A. Back et al. improved the hard x-ray production by an order of magnitude while irradiating the high-Z gas with the high-power laser because less energy is lost to kinetic energy and sub-keV x-rays compared with the solid targets [1]. In our previous studies, the laser to x-ray conversion efficiency was simulated for the high-Z gold foam targets with different initial density. It has been shown that the conversion efficiency was increased in the energy range from multi-eV to multi-keV, which is caused by both the increase of laser absorption and reduction of ion kinetic energy for the low initial density [19,20]. However, as far as we know, the further enhancement of the laser to x-ray conversion efficiency for high-Z mixture with low initial density, has still not been studied up to now, especially in the photon energy range from multi-eV to multi-keV, which is very critical to the indirect drive ICF research.

In this letter, low-density high-Z mixture targets are proposed to increase the laser to x-ray conversion efficiency in the photon energy range from multi-eV to multi-keV. The conversion efficiencies and x-ray spectra for the laser-irradiated pure gold and Au–Gd mixture targets with different initial densities have been

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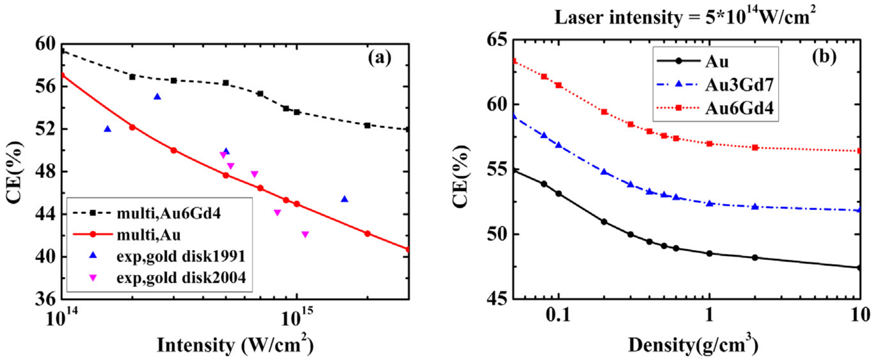

Fig. 1. (a) Intensity-dependent laser to x-ray CE for the Au and the Au–Gd mixture (6/4) from simulations. The lower triangles and upper triangles correspond to the experimental results of Refs. [3] and [23], respectively. (b) Density-dependent CE from simulations for the Au and the Au–Gd mixture at two mixing ratios of 3/7 and 6/4 when a constant-power laser focused to 5×10^{14} W/cm^2 is used.

simulated. Further enhancement of the conversion efficiency was obtained by using the Au–Gd mixture with low initial density.

2. Simulation results

Simulations were performed with the widely used one-dimensional multi-group radiation hydrodynamics code Multi-1D [21]. Radiation and electron thermal transport equations are coupled with the hydrodynamic equations and the inverse bremsstrahlung is included in the laser energy deposition in Multi-1D. In the simulations, data of equation of state (EOS) were from the SESAME database and radiation opacities in non-local thermodynamic equilibrium were from tabular data, which were calculated with the code SNOP [22], for pure gold target. But for mixtures of Au and Gd, the densities of the two constituents were determined at first in a self-consistent manner assuming that the two constituents of the mixture were in pressure and temperature equilibrium. Then, both the equation of state and radiation opacities for the mixture were calculated from the combination of Au and Gd data with the constituent fraction as a weighting factor. For radiation thermal transport, the photon energy of the radiation ranged from 0.1 to 5 keV was divided into 100 energy groups. The electron thermal conduction was described by the interpolation between the Spitzer's regime and the flux limited regime and the flux limiter was set as 0.03.

In the simulations, 1 ns flat top 351 nm lasers with different intensities were supposed to be incident on planar targets. The laser to x-ray conversion efficiency ($\mathrm{CE} = E_X/E_L$) were investigated for the pure gold and the Au–Gd mixtures with different initial densities at different laser intensities. Here E_L, and E_X express total laser energy, and total radiation energy, respectively. The intensity-dependent CEs, which were integrated over 3 ns in time covering x-ray photon energy of 0.1–5 keV, for the mixture of Au–Gd with atomic ratio of 6/4 and the gold (represented by the mixture of Au/Gd = 99/1) are illustrated in Fig. 1(a). It shows that the conversion efficiencies for the pure gold and the Au–Gd mixture decrease as the laser intensity increases from 1×10^{14} W/cm^2 to 3×10^{15} W/cm^2, which is consistent with the previous results [6]. The x-ray conversion efficiencies from several gold-disk experiments with a 351 nm laser irradiation in the past [3,23], are also plotted in Fig. 1(a), which are in good agreement with our simulation results. Moreover, the Au–Gd mixture (6/4) has a slower decrease and a more significant enhancement of CE as the laser intensity increases comparing with the pure gold. This may be partly due to the contribution of M-band radiation of the Gd, which is more obvious at higher laser intensity.

Fig. 1(b) presents the overall x-ray CE for the pure Au and the Au–Gd mixtures at two mixing ratios as a function of the target initial density at the incident laser intensity of 5×10^{14} W/cm^2.

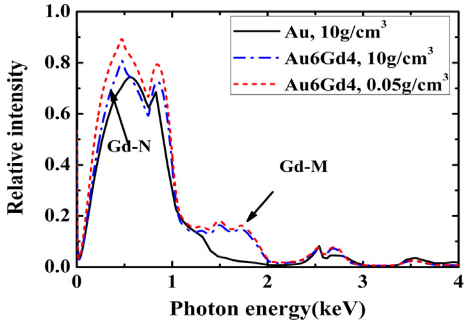

Fig. 2. The relative x-ray emission spectra integrated over 3 ns in time for the three types of targets from simulations. The three targets are 10 g/cm^3 Au, 10 g/cm^3 Au–Gd (6/4) mixture, and Au–Gd (6/4) mixture foam with a density of 0.05 g/cm^3.

The laser to x-ray conversion efficiencies increase as the initial density decreases for all the three targets and almost the same CE increases due to initial density effect have been shown in Fig. 1(b). In the whole initial density range of 0.05–10 g/cm^3, the conversion efficiencies for the two mixtures of Au–Gd (3/7) and Au–Gd (6/4) are larger than those for the pure gold. Fig. 1(b) also shows that the mixture of Au–Gd (6/4) has the larger CE than the Au–Gd (3/7) mixture, which owns to almost the maximum Rosseland mean opacity of the Au–Gd (6/4) mixture [24]. The x-ray CEs for the pure Au and the Au–Gd mixture (6/4) at initial density of 10 g/cm^3 are 47.4%, and 56.3%, respectively. A CE enhancement of 8.9% is achieved for the mixture of Au–Gd (6/4). Furthermore, as the initial density decreases from 10 g/cm^3 to 0.05g/cm^3, the x-ray CE for the mixture of Au–Gd (6/4) increases from 56.3% to 63.4%, getting a 7.1% further enhancement. Therefore, 16% absolute CE increase has been obtained in total for the high-Z mixture of Au–Gd (6/4) with low initial density of 0.05 g/cm^3, comparing with the pure gold of 10 g/cm^3. It means that the CE for the low-density Au–Gd mixture is 1.34 times of that for the pure gold.

Time-integrated x-ray emission spectra for the three types of targets are plotted in Fig. 2. It is observed that the x-ray emissions for the Au–Gd (6/4) mixture of 10 g/cm^3 is enhanced by almost 140% in the spectral region 1.2–2 keV and only about 10% in soft x-ray region of < 1 keV, comparing with the pure Au of the same density. In fact, 54% of the total enhancement comes from the spectral region 1.2–2 keV. However, as the density decreases from 10 g/cm^3 to 0.05 g/cm^3, the x-ray emissions almost have no increase in the spectral region of 1.2–2 keV, but 13.6% enhancement are obtained in soft x-ray region of < 1.0 keV. Therefore, the enhanced emission for Au–Gd mixture (6/4) is mainly attributed to the x-ray emission of Gd plasmas in the photon energy region of 1.2–2 keV. In addition, x-ray emission enhancement is achieved