Efficient soft x-ray sources from laser-irradiated gold foam targets with well-controlled impurities

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Abstract
As an important x-ray source, enhancement of x-ray emissions from laser-produced plasmas is significant for various applications. Due to less expanding kinetic loss, gold foam with low initial density can have an enhanced x-ray conversion efficiency compared with solid-density gold. However, low-Z impurities within gold foam targets will diminish the enhancement remarkably, and should be tightly controlled. This paper presents an experimental study of a high brightness laser plasma soft x-ray source, based on a 0.36 g cm$^{-3}$ gold foam target with negligible impurities irradiated by nanosecond laser pulses with power density around $3 \times 10^{14}$ W cm$^{-2}$ at the Shenguang II laser facility. A conversion efficiency, from multi-eV to multi-keV, of 51.2% is achieved in the x-ray emissions—about 21% relative enhancement compared with a solid-density gold target, and the highest conversion efficiency for Au foam planar targets yet. Good agreement has been achieved between the semi-analytical model prediction and the experimental results.

Keywords: Au foam, enhanced soft x-ray source, impurities

(Some figures may appear in colour only in the online journal)
than that of solid-density gold, [23] and previous simulations have demonstrated higher soft x-ray conversion efficiency from laser-irradiated high-Z foam targets [24–26]. The enhancement is theoretically caused by both the increase of the laser absorption and the reduction of ion kinetic energy for the low initial density. A gold foam target has also been demonstrated experimentally to show the enhanced x-ray re-emission feature [27].

High-Z foam targets are hence predicted to be very favorable for indirect ICF, with good conversion efficiency and improved symmetry control [28]. Several other targets, including high-Z mixture target [29, 30], even high-Z mixture foam target [31], double-foil gold target [32], and so on [33], have also been put forward as high brightness x-ray sources.

Due to the development of manufacturing capabilities to produce Au foam targets with ultra-low initial densities, related experiments are practicable at the research center of laser fusion (LFRC) in China. However, in previous related experiments, the conversion efficiency of the Au foam targets were even lower or provided limited enhancement, compared with the solid-density Au targets [34, 35], mainly due to the important effect of low-Z impurities within the targets. These low-Z impurities are unavoidable in the manufacturing process at present, and we have developed a general easy-to-use semi-analytical model based on hydrodynamic simulations to evaluate the important quantitative impact of the impurities on the x-ray conversion [36]. Accordingly, in order to obtain enhanced high brightness soft x-ray sources, the impurity content should be controlled to an ignorable level.

In this paper, we present experimental studies using Au foam targets with well-controlled impurities, performed recently at the Shenguang-II laser facility. The target is a significant advance, due to its low density and negligible impurities. The aim of the studies is to characterize the enhanced soft x-ray emissions from Au foam targets irradiated by 1 ns laser pulses with power density around $3 \times 10^{14} \text{ W cm}^{-2}$. Strong production of the soft x-ray spectrum, and a total conversion efficiency (CE) over 51% are measured from the 0.36 g cm$^{-3}$ Au foam planar target with fewer impurities, and the CE is even higher than that of the previous 0.25 g cm$^{-3}$ Au foam planar target [35]. This phenomenon is reproduced well by the impurity model analysis, and it is demonstrated experimentally that a gold foam target with well-controlled impurities can increase the laser to x-ray conversion efficiency as predicted.

2. Experimental setup

The experiments were conducted on the Shenguang-II laser facility. A schematic of the experimental layout and plot of the laser temporal profile—identical with those of [30, 35]—are shown in figure 1. The plasma is produced by irradiating the solid-density gold planar targets or the Au foam planar targets normally with the intense frequency-tripled (351 nm wavelength) beam nine laser, which is smoothed by the lens array (LA). The quadrature laser spot focused on the target front is about 420 $\mu\text{m} \times 420 \mu\text{m}$ (full width at half-maximum). The laser energy, typically ~500 J in ~1 ns of a flat-top pulse to produce an irradiance of about $3 \times 10^{14} \text{ W cm}^{-2}$, which is common to all targets, is shown in figure 1(b).

An x-ray pinhole camera (XPHC) is used to diagnose the laser spot, and two typical measured spots for the solid-density Au and the 0.36 g cm$^{-3}$ Au foam target are exhibited in the upper right of figure 1(a). A transmission grating spectrometer (TGS), with spectral resolution of 0.1 nm over the wavelength range of 0.25–25 nm, is used to record the time-integrated x-ray emission spectrum from the laser-produced plasmas at 46.6° with respect to the target normal. The relative uncertainty of the x-ray spectrum by TGS is lower than 10%. The angular distributions of the laser plasma x-ray emissions are measured using flat-response x-ray diodes (FXRDs) at five different angles to the target normal, including 22.5°, 26.8°, 41°, 45°, and 68.3°. Previous studies showed that the FXRD had response flatness smaller than 13% in the photon energy range of 0.1–4 keV [37], relative uncertainty of the x-ray flux lower than 12% and a temporal resolution of about 170 ps. Both TGS and FXRD have been absolutely calibrated, for a quantitative measurement.

At present, two different manufacturing methods can be employed to prepare the low-density Au foam targets, with different initial densities and impurity contents. By using the first method (named the ‘ec’ method hereafter), the monolithic foamed gold is synthesized by a template deposit-dealloying method with polystyrene (PS) template and gold silver electroless depositing and dealloying [38]. For the second method (named the ‘nm’ method hereafter), gold nano-particles with small grain sizes and good solubility are prepared and used as starting building blocks; afterwards, the freeze-dry technique is employed to prepare gold compound foams and finally the gold compound foams are sintered to obtain porous gold foams with ultra-low density [39]. Nevertheless, there are unavoidable low-Z inclusions during these two manufacturing methods, like C, H, O, S. Compared with the ‘nm’ method, the Au foam targets made by ‘ec’ method have fewer impurities, but its lower foam density limit is a little higher. The lowest Au foam density by ‘ec’ method at present is 0.36 g cm$^{-3}$ used in this work, while that by ‘nm’ method was 0.25 g cm$^{-3}$ used in [13].

The proportions of all elements for the different Au foam targets, listed in table 1, are measured by means of inductively coupled plasma (ICP), energy dispersive spectrometry (EDS), and the burning method. Several previous Au foam targets are also listed for comparison. It is shown that the primary element of the impurities is O. The micro-structure of the Au foam targets is measured by the scanning electron microscope (SEM), as shown in figure 2. Due to the distinct preparation techniques, there are different porous structures of the Au foam targets for the two methods. In addition, solid-density Au targets are used as the benchmark for comparison of these Au foam targets in the experiments.

3. Results and discussion

3.1. X-ray spectra

The x-ray spectra of the various planar targets are unfolded by the iterative procedure of the TGS results. The inset of figure 3 shows the primary uncorrected x-ray spectroscopy of the solid
However, an abrupt drop around 300 eV, not a feature of the Au plasmas, is clearly seen in the spectroscopy. This is mainly due to the contamination of mechanical oil on the surface of the charge-coupled device (CCD), the carbon element of which causes an absorption edge around 280–300 eV [40]. In order to obtain the real x-ray spectrum, we consider the oil contamination as a layer of C filter, the thickness of which is inferred as 28 nm from the dropping range around 300 eV of the primary uncorrected x-ray spectroscopy.

With the response correction from multi-eV to multi-keV caused by the oil contamination, the real x-ray spectra of laser plasmas from the targets are illustrated in figure 3. The dominant emissions in the soft x-ray region 0.1–2 keV, with small contributions of x-ray emissions from Au-M band, is observed.
from the solid-density Au targets. The x-ray emission intensities from the Au foam targets of the 0.36 g cm\(^{-3}\) by ‘cc’ method and the 0.25 g cm\(^{-3}\) by ‘nn’ method are both higher than that of the solid-density Au target, indicating enhancement of the x-ray source due to the low initial density effect, especially in the soft x-ray region. This is consistent with theoretical expectations. According to our previous studies, it was confirmed that the radiation heat wave is subsonic for the solid gold target, while supersonic for Au foam targets with initial density lower than 1 g cm\(^{-3}\) [26]. As to the Au foam targets, the shock wave behind the supersonic radiation heat wave produces an additional net outward radiation for the enhancement of the x-ray emission in the soft x-ray region.

Compared with the 0.25 g cm\(^{-3}\) Au foam produced by the ‘nn’ method, the 0.36 g cm\(^{-3}\) Au foam produced by the ‘cc’ method—with higher initial density but lower impurity contents—has apparently more x-ray emissions in the soft x-ray region, indicating the significant impact of low-\(Z\) impurities on the x-ray conversion of Au foam targets.

### 3.2. Total x-ray conversion efficiency

The total x-ray conversion efficiency (\(\eta_X\) or CE) is defined as the ratio of the overall x-ray emissions to the input laser energy, and can be inferred from the x-ray angular distributions. Generally, the x-ray emissions for the planar targets are reduced away from target normal and can be fitted with the expression of \(I_0 = \beta \cos^\alpha (\theta)\). Here, \(\theta\) is the angle to the target normal, and \(\alpha, \beta\) are constants.

In the experiments, the angular distributions of the laser plasma x-ray emissions are measured with five FXRDs at different angles. On account of the FXRD results and the integrated x-ray emissions from the TGS, there are two possible ways to determine the overall x-ray conversion efficiencies of all targets.

By the fit of the experimental FXRD results to the analytical expression \(\beta \cos^\alpha (\theta)\), the constants \(\alpha, \beta\) can be obtained. Then \(\eta_X\) and the uncertainty are determined in the first way as follows:

\[
\eta_X = \frac{2\pi \beta}{(\alpha + 1)E_L} \quad (1)
\]

\[
\frac{\sigma_{\eta_X}}{\eta_X} = \sqrt{\left(\frac{\sigma_\beta}{\beta}\right)^2 + \left(\frac{\sigma_\alpha}{\alpha + 1}\right)^2 + \left(\frac{\sigma_{E_L}}{E_L}\right)^2} \quad (2)
\]

The relative uncertainty of the laser energy is thus determined at a level of about 5%, and the uncertainties of \(\alpha, \beta\) are obtained by the fit process.

In the second way, the x-ray emissions (\(I_0\)) from the TGS location are spectrally integrated from the time-integrated x-ray spectroscopy. Together with the angular distribution fitted by the FXRD results, the \(\eta_X\) and the uncertainty can also be expressed as

\[
\eta_X = \frac{2\pi I_0}{(\alpha + 1)E_L \cos^\alpha \theta} \quad (3)
\]

#### Figure 3. Time-integrated x-ray spectrum of solid gold (shot 115), 0.25 g cm\(^{-3}\) Au foam (shot 108) [35] and 0.36 g cm\(^{-3}\) Au foam (shot 111). Inset shows the uncorrected x-ray spectrum of solid gold.

\[
\frac{\sigma_{\eta_X}}{\eta_X} = \sqrt{\left(\frac{\sigma_{I_0}}{I_0}\right)^2 + \left(\frac{\sigma_\alpha}{\alpha + 1}\right)^2 + \left(\frac{\sigma_{E_L}}{E_L}\right)^2 + \left(\frac{\sigma_{\cos^\alpha \theta}}{\cos^\alpha \theta}\right)^2} \quad (4)
\]

The relative measurement uncertainty of \(I_0\) is thus estimated at about 10%; the uncertainties of the laser energy and \(\alpha\) are the same as in equation (2).

Figure 4 illustrates the total laser to x-ray CEs of the Au foam and the solid-density Au targets in the experiments by equations (1)–(4). For different shots under the same condition, the CEs obtained are all within the error bars. As to the different targets, although the experimental CEs may incline to the same value if we include the error-bars, the same trend is shown by the average values of CEs obtained by the TGS and XRD. It is confirmed that the average CE values for the Au foam targets are all higher than those of the solid-density Au targets. On the one hand, when comparing Au foam targets made in the same way, the CE increases as the density decreases, as expected. On the other hand, however, the total CE of the 0.25 g cm\(^{-3}\) ‘nn’ method Au foam is lower than that of the 0.36 g cm\(^{-3}\) ‘cc’ method Au foam, identically to the spectrum results and mainly due to the impact of low-\(Z\) impurities, as we will discuss below.

### 3.3. Semi-analytical model of impurity analysis

At present, low-\(Z\) impurities are unavoidable in the manufacturing processes of the Au foam targets. The trouble with these low-\(Z\) impurities is that they are highly or even fully ionized, and contribute about twice the degrees of ionization per unit weight as the Au element, thus raising internal energy by increasing the specific heat [41]. In addition, much less radiation is obtained from low-\(Z\) impurities, due to the much lower mean Rosseland opacities. In order to evaluate the quantitative impact of impurities within the gold foam target on the laser to x-ray CE, a general easy-to-use semi-analytical model based on the hydrodynamic simulations has already been developed [36].
In the energy balance of laser interaction with a high-Z planar target, almost all the absorbed laser energy is divided into three leading portions

\[ \eta_a = \eta_X + \eta_K + \eta_I \]  

(5)

here \( \eta_X, \eta_K, \) and \( \eta_I \) express the total radiation energy, internal energy, ion kinetic energy, and the absorbed laser energy, respectively, all normalized to the input laser energy.

The presence of impurities will influence the emissivity, the specific heat, and will also probably change the plasma states. First, compared with high-Z material, low-Z impurities radiate much less, and the decrease of radiation is hence linear with the impurity contents by mass. Second, the target specific internal energy increases due to the impurities, which may lead to a different plasma state. The variation of the radiation depends on both effects. The modified CE for the target with impurities can then be obtained as (the superscripts mix, im, Au stand for gold foam with impurities, impurities alone, and pure gold foam respectively) \[36\]

\[ \eta_{\text{mix}} = \eta_X \left( 1 - \sum_n \beta_n^{\text{im}} \right) \left( 1 + \sum_n \beta_n^{\text{im}} \right) \frac{\eta_X (K + 1) \sum_m \theta_m^{\text{im}}}{\eta_X + \eta_K + \eta_I} \]  

(6)

\[ = \eta_X \left( 1 - \sum_n \beta_n^{\text{im}} \right) \left( 1 + \sum_n \beta_n^{\text{im}} \right) \]  

(7)

Here, \( \beta_n^{\text{im}} \) represents the fractional weight of the impurity type \( n \) (of \( m \) types in total). The coefficient \( k_n \), which equals \( e_n^{\text{im}}/e_n^{\text{Au}} - 1 \) (\( e \) being the specific heat), expresses the increase extent for the specific internal energy of the \( n \) type impurity to that of pure gold, under given plasma conditions. If an impurity had twice the specific heat as \( \text{Au} \), then \( k_n \) would be 1. However, \( k_n \) depends on the temperature and density of the plasma, which changes in space and time as the target is heated. Therefore equation (6) should be evaluated using a weighted mean \( \bar{k} \) that is averaged over the spatial profile of the heated plasma at each time. Moreover, if we define a calculated weighted coefficient \( \bar{K} = \sum_m k_m \theta_m^{\text{im}} / \sum_m \theta_m^{\text{im}} \), equation (6) can be rewritten as equation (7), which depends on the total fraction of all impurities. In fact, \( \bar{K} \) means the increase extent for the averaged specific internal energy of all impurities to that of pure gold.

To compare our model predictions with the experimental results, the energy distributions of the laser conversion are the

Figure 4. Total CEs for the various targets. (a) the XRD results by equations (1) and (2); (b) the TGS results by equations (3) and (4). The solid lines express the average value for the same targets over multiple shots.

Figure 5. Energy percents of laser conversion versus time with (a) the 0.25 g cm\(^{-3}\) Au foam target by ‘nm’ method and (b) the 0.36 g cm\(^{-3}\) Au foam target by ‘ec’ method. All the lines have been normalized to the time-integrated incident laser energy at the given time. The temporal evolution of the weighted linear coefficient was also plotted. Since the dominant impurity is O for both targets, the \( K \) are very close.
prerequisite. Therefore, the simulations are performed with the widely used multi-group radiation hydrodynamics code Multi-1D [42]. The equation of state for Au is taken from the SESAME database, and the opacities are calculated by the code SNOP [43]. In the simulation, the photon energy of the radiation ranging from 0.1 to 5 keV is divided into 20 energy groups. In addition, the flux limiter is set at 0.03. Figure 5 shows the temporal evolution of the laser energy conversion and the calculated weighted coefficient $K$, for Au foam targets of the 0.25 g cm$^{-3}$ by ‘nm’ method and the 0.36 g cm$^{-3}$ by ‘ec’ method. By inserting these quantities of figure 5 into equation (7), we can estimate the impact of the impurities within the Au foams on the x-ray conversion quantitatively. For the 0.25 g cm$^{-3}$ Au foam target, the modified fraction of the radiation energy (or modified CE) in figure 5 is apparently lower than that of the ideal Au foam target, due to the $\sim 15\%$ impurity content from table 1. However, as negligible impurity is introduced in the manufacturing processes, the modified CE of the 0.36 g cm$^{-3}$ Au foam target by ‘ec’ method is only a little lower, but basically overlapping with the ideal case.

### 3.4. Comparison of CEs between model predictions and experimental results

The simulated CEs can be modified with the impact of impurities taken into consideration, according to the analytical model and hydrodynamic simulations; the comparisons with the experimental results are shown in figure 6. After the modification due to the impact of impurities, the CEs obtained from the TGS and XRD track each other closely as well as the predictions by the analytical model with the hydrodynamic code, for the gold foam targets.

Using the 0.36 g cm$^{-3}$ ‘ec’ method Au foam target, the CE of the x-ray emissions from multi-eV to multi-keV is achieved as 51.2% (an average of the TGS and XRD results), up to 21% experimental enhancement relatively compared with the solid gold target, and is the highest conversion efficiency for Au foam planar targets yet. It is experimentally demonstrated that the Au foam target with well-controlled impurities can increase the laser to x-ray CE, as predicted.

Figure 6 also illustrates that the relative enhancement was less than 11% for the 0.25 g cm$^{-3}$ ‘nm’ method Au foam target, which was the lowest foam density tested [35]. This only matches with the effect of the ‘ec’ method Au foam target, with much higher initial density 1 g cm$^{-3}$. Therefore, minimization of low-Z impurities is needed to take full advantage of low initial density Au foam targets as enhanced laser plasma x-ray sources.

From figure 2, the Au foam targets are all prepared with the porous structures, which are beneficial for laser trap and absorption. To penetrate through, the laser has first to heat them and wait until the density decreases down to the critical density, due to structural expansion. In the plasma region under the critical density, the laser absorption is distributed over the foam volume providing conditions for efficient plasma smoothing of the laser light. Therefore, a higher laser absorption coefficient is expected for the Au foam targets, and this is verified by the lower backward scattered light measured in the experiments. However, the device used in the scattering measurement was then not absolutely quantitative. On account of the relative comparison of the scattering measurements, a modified laser absorption coefficient of 0.94 is used for the solid-density Au target when that of the foams is assumed as 1, to amend the simulation results.

As a further matter, for the pure Au foam with an initial density of 0.1 g cm$^{-3}$, up to 30% relative CE enhancement can be obtained compared with the solid-density Au targets, from 42.4% to 55.1%, mainly caused by the soft x-ray emissions. This high brightness soft x-ray source is of significance in applications to ICF, HEDP, etc.—although further experiments are still essential.

### 4. Conclusions

Experimental studies of soft x-ray sources using solid-density Au and Au foam planar targets with well-controlled impurities irradiated by nanosecond laser pulses with energies $\sim 500$ J from the Shenguang-II laser facility have been performed. The aim of the work is to develop a high-brightness laser-plasma soft x-ray source using low initial density Au foam targets in the applications of ICF and HEDP.

Soft x-ray emissions from the planar targets were measured using absolutely calibrated TGS and FXRDs. Two different manufacturing methods can be employed to prepare the low-density Au foam targets, with different initial densities and impurity contents. According to the spectral characteristics measured by the TGS, the dominant emissions in the soft x-ray region (1–2 keV) is observed from the solid-density Au targets and enhanced using the Au foam targets of 0.36
g cm\(^{-3}\) by \textit{ec} method. The total CEs are inferred from the x-ray angular distributions. In addition, a general easy-to-use semi-analytical model \cite{36} based on the hydrodynamic simulations is used to evaluate the quantitative impact of the impurities, which are unavoidable at present during the manufacturing processes. The CEs obtained from the TGS and XRD track each other, as well as the predictions of the manufacturing processes. The CEs obtained from the TGS simulations is used to evaluate the quantitative impact of using semi-analytical model \cite{36} based on the hydrodynamic x-ray angular distributions. In addition, a general easy-to-

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