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X-ray reemission from CH foils heated by laser-generated intense thermal radiation

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X-ray emission and burn through of radiatively heated plastic foils have been investigated in a gold cavity heated by eight beams of the Gekko XII laser up to a radiation temperature of 140 eV. We measured the temporally resolved reemission spectra of carbon. The time and frequency integrated reemission was 23% of the gold reemission. The measurements are in good agreement with numerical simulations.

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Radiative heating of solid matter by the intense x rays generated by laser irradiated high-Z targets results in a uniform hot dense plasma. This allows one to study experimentally x-ray opacities and radiative transport in a regime that was previously not accessible in the laboratory [1–10]. These studies are of great interest in astrophysics, where accurate and experimentally checked opacities are needed for modeling the evolution and structure of stars [11]. Another important application of radiative heating is indirectly driven inertial confinement fusion (ICF) [12]. In this case the intense x rays generated in a high-Z cavity ablate the low-Z wall of a deuterium-tritium pellet, leading to its compression and eventually to thermonuclear burn. For this application it is crucial to know the properties of the radiatively heated layer, such as its thickness and temperature. In particular, the reemission of x rays from the heated pellet wall is important, because it strongly affects the coupling of energy into the pellet and the distribution of the radiation energy in the cavity [13,14]. In order to keep the reemission small, one has to choose a wall material of low nuclear charge Z.

Characteristic of radiative heating is the propagation of x rays into the wall under the influence of the decreasing opacity due to the heating and ionization of the matter. As a result, an ablative temperature wave propagates into the wall, which has been studied theoretically [15,16]. Detailed experimental investigations have been performed with high-Z material at temperatures up to 240 eV [3,4]. Experimental studies with low-Z material were limited to modest temperatures well below 100 eV corresponding to x-ray fluxes lower than 10^{13} W/cm^2. Radiative burn through has been observed in 0.8-μm-thick Be foils and 1-μm-thick plastic foils [8,9]. A direct measurement of the temperature of $\approx$40 eV in a radiatively heated plastic foil by absorption spectroscopy has been performed by Edwards *et al.* [5]. A first attempt to measure the frequency integrated reemission from a radiatively heated wall of varying Z showed an increase of the reemission with Z [17].

In this paper we present a temporally resolved spectroscopical study of the radiative heating of low-Z matter at higher radiation temperatures exceeding 100 eV by focusing the beams of the Gekko XII laser into a gold cavity and by heating thin plastic foils (CH) with the intense x rays generated therein. Besides the investigation of the radiative burn through, we present a spectrally and temporally resolved measurement of the reemitted radiation. The simple spectroscopic structure of the carbon wall material facilitates the comparison with calculations.

The experimental arrangement is illustrated in Fig. 1. Eight beams of the Gekko XII laser (a total of 4 kJ of 0.35-μm light in 0.8 ns) were focused in a specially formed gold cavity converting a high fraction of laser light to x rays. The beams hit the wall of the converter part of the cavity at such an angle that neither the direct nor the reflected laser light could heat the central cylindrical part of the cavity where the sample was situated. Thus the sample was heated essentially by thermal x rays emitted from the hot gold wall of the cavity. The central part of the cavity was a cylinder of 1 mm length and 1 mm diameter. Two diagnostic holes of a diameter of 400 μm were situated opposite each other. The reemitter foil was glued onto a hole (1), as shown in Fig. 1. It was chosen to be thick enough ($\geq$6 mg/cm^2) to absorb all the heating x rays. The other hole (2) served as a diagnostic hole for the reemitted radiation. Thus x-ray reemission was observed by looking through the cavity. To avoid edge effects from the diagnostic hole, a diaphragm of a smaller diameter of 200 μm was positioned at 0.7 mm distance from

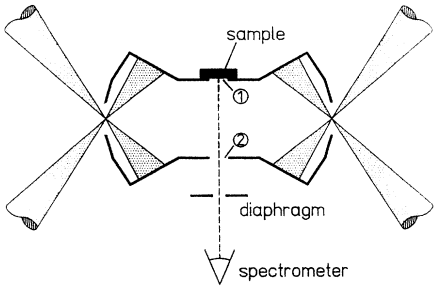

FIG. 1. Arrangement of the gold cavity used to study the reemission from a radiatively heated sample.

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the diagnostic hole. We studied radiative burn through of plastic absorber foils, too. In this case, hole (1) was closed by a gold emitter and the absorber foil was glued onto diagnostic hole (2). Due to the strong heating by intense x rays from the cavity a thin enough burn-through foil became transparent.

To measure the reemitted or transmitted radiation we used a 5000-line/mm transmission grating spectrometer with an x-ray streak camera (XRSC) [18] as a detector. The spectral resolution was 0.07 nm and the temporal resolution was 30 ps. As the material to be investigated was carbon, we prepared the photocathode of the streak camera by CsI evaporated on a thin aluminum substrate. This type of photocathode is nearly as sensitive as the generally used CsI evaporated on carbon, and its spectral response does not contain the carbon K edge within the range of investigation. Because it was not easy to fabricate a cathode of good homogeneous structure, we selected from a larger number a sample as homogeneous as possible.

The reference for both, the reemission and the burn-through experiments, was the x-ray emission from the x-ray heated gold on hole (1) observed through the open hole (2). In addition, the radiation of the gold wall was monitored in each shot through another diagnostic hole (not shown in Fig. 1) by a second XRSC in a 1000-lines/mm transmission grating spectrometer and a time-integrated pinhole-grating spectrometer with absolutely calibrated x-ray film as detector. We obtained an x-ray pulse of 700 ps full width at half maximum duration with a brightness temperature of 125 eV.

The result of the radiative burn-through experiment is illustrated in Fig. 2(a). It shows a typical transmission spectrum of a 5-μm-thick parylene foil (C_8H_8) at 0.2 ns after the peak of the x-ray pulse (the time $t=0$ refers to the maximum of radiation emitted from the gold wall in the following). At this time ($t=0.2$ ns) the foil is totally transparent for photon energies below the cold carbon K edge (284 eV), whereas the transmission of the cold foil is $\approx 20\%$ here. The region above the K edge becomes transparent, showing an absorption spectrum characteristic of highly ionized carbon. The strongest absorption lines are the He-like $1s^2$–$1s2p$ (He α) and $1s^2$–$1s3p$ (He β) transitions. Between these two absorption lines there is a transmission window (marked as W1), which reaches 70% transmission in contrast to the cold foil for which the transmission is less than 10^{-6} here. The strong heating of the material is underlined by the appearance of the hydrogenlike Ly-α and Ly-β absorption lines. Between these lines another transmission window (marked as W2) can be observed. The inset in Fig. 2(a) illustrates how these two transmission windows open with time. The H-like window W2 appears with a delay of 200 ps after the He-like window W1. The foil starts to become transparent near the peak of the x-ray pulse. A weak burn through was observed in a thicker, 8-μm plastic foil. It starts to become transparent in the He-like window W1 only late at the end of the pulse, and the H-like window W2 does not appear at all.

From these observations we conclude that a 5–10-μm-thick plastic layer is radiatively heated and transformed into highly ionized carbon. We note that the structure of the transmission spectrum is quite similar to that observed previously with beryllium at lower temperatures [9].

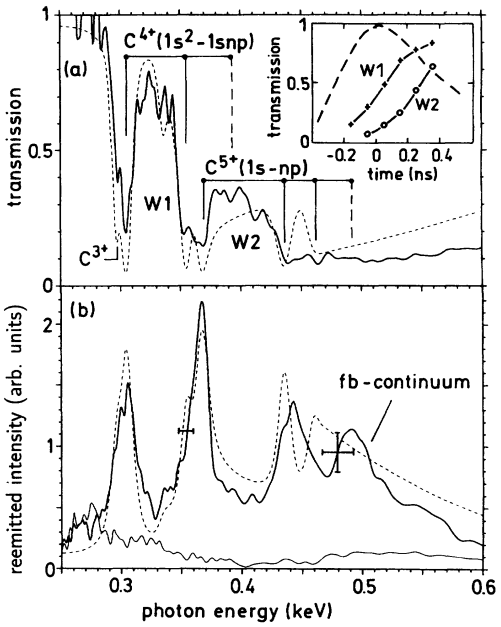

FIG. 2. (a) Transmission spectrum of 5-μm-thick parylene observed at 200 ps (solid line). The inset shows the time dependence of the burn through in the transmission windows between the $1s^2$–$1s2p$ and $1s^2$–$1s3p$ transitions (W1) and between the $1s$–$2p$ and $1s$–$3p$ transitions (W2) together with the reference pulse (in arb. units) reemitted from gold. (b) Measured carbon reemission spectrum (solid line). The thin line shows the background emitted by the gold plasma filling the cavity. The dashed spectra in (a) and (b) are calculated. The measured and calculated spectra in (b) are normalized to the same area under the spectrum (fb continuum is the free-bound continuum).

Figure 2(b) shows the carbon reemission spectrum averaged for 0.6 ns duration from $t=-0.35$ ns until $t=0.25$ ns. The horizontal error bars in the figure illustrate the experimental spectral resolution. The vertical error bar at 0.48 keV corresponds to a local inhomogeneity of the cathode (note that the inhomogeneity plays a role only here; at other spectral regions this error was less than 5%). It is important to check the eventual contribution from gold plasma filling the cavity. For that purpose the carbon reemission spectrum is compared here with a spectrum obtained by looking through the two open holes (1) and (2), in which case only the radiation of the plasma filling is seen. We find that the radiation of the plasma filling disturbs only below 0.28 keV and above 0.6 keV, thus out of the most important range of the carbon spectrum. (Moreover, it is noted that with the carbon reemitter the background from gold filling seemed to be suppressed, as was judged from the XRSC pictures. The cause of it may be that the fully stripped light carbon ions fill up the cavity faster, preventing its filling with the partially stripped heavy Au ions.)

The observed carbon spectrum is dominated by broad lines (He α, Ly-α, and Ly-β) and a strong contribution from the free-bound (fb) continuum. It is characteristic of the emission from a thick hot carbon layer. Because of its increasing temperature and thickness with time the spectrum

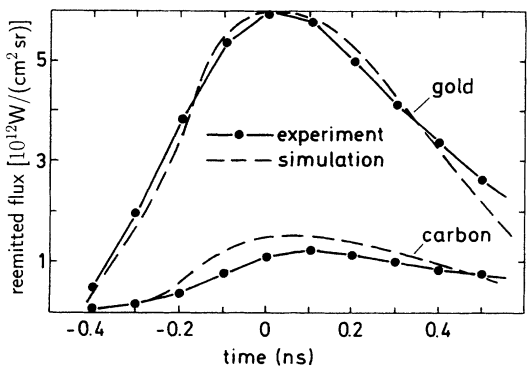

FIG. 3. Time dependence of the radiation reemitted from gold and carbon integrated in the spectral range of 250 eV to 1 keV. The experimental results (solid lines) are compared with calculations (dashed lines). The absolute scale for the ordinate was obtained from the time-integrated measurement on calibrated x-ray film.

showed a time dependence. At the beginning ($t \lesssim -0.35$ ns) the He α and Ly-α lines have the same height, and the He β line is still separated from the Ly-α line. Later on, the Ly-α line becomes dominant and the He β line appears only as a shoulder of the Ly-α line. The fb continuum is small in the beginning and increases with time due to the increasing thickness of the heated layer. The temporally averaged spectrum in Fig. 2(b) is characteristic of the main period of emission, during which time the spectrum practically does not change.

A comparison of the frequency integrated reemitted flux from a gold and a carbon wall is shown in Fig. 3, where it is plotted versus time. The maximum of the carbon reemission appears somewhat later than that of gold. The ratio of the reemitted flux of carbon and gold increases with time from 10% to 30%. The time integrated reemission of carbon is 23% of the gold reemission. (We note, that the corresponding value found by Nishimura *et al.* [17] is approximately a factor of 5 to 10 lower. One reason for this difference may be the lower temperature of the experiment of Ref. [17].)

In order to compare the experimental results with theory we have performed one-dimensional numerical simulations in planar geometry with the MULTI computer hydrocode [19]. The emitted radiation has been calculated by a post processor, which solves the radiation transport equation for the temperature and density profiles calculated by MULTI and which yields better spectral resolution than the multigroup diffusion approximation of MULTI. The opacities were obtained by the SNOP code [20]. In the regime of this experiment the carbon opacity is dominated by bound-free transitions, the cross sections of which values have been taken from Ref. [21], and, in particular, by electron impact broadened line transitions with a Lorentz profile [22]. Local-thermal-equilibrium (LTE) values of the opacity are used. The choice of LTE can be considered as a useful approximation, although for the present condition the collisional rates no longer guarantee LTE. However, photoionization and excitation caused by the intense radiation field bring the plasma into a state fairly close to LTE. This has been confirmed by means of the RATION code [23], which considers these processes (in contrast to the SNOP code).

Another idealization concerns the source radiation which is incident on the wall of the sample. It was approximated by a Planckian (isotropic) source. Its temperature has to exceed the measured gold wall temperature, because the gold wall does not completely reemit the incident source radiation. A source temperature of 138 eV yielded the measured gold wall temperature of 125 eV corresponding to a gold reemission of 70% of the source radiation. The source was modulated temporally in such a way that it reproduced the measured pulse emitted from the gold wall. The agreement shown in Fig. 3 was achieved with an asymmetric source pulse of 0.3 ns rise and 0.9 ns fall time.

This source radiation was then applied to heat a carbon foil. In a thick foil (which does not burn through) it generates a hot dense layer of 115 eV maximum temperature, of a density around 0.1 g/cm^3 and of a thickness growing with time to 0.7 mg/cm^2 (corresponding to 7 μm in the cold solid foil). Calculated spectra of the transmitted and reemitted radiation are plotted in Fig. 2 (the dashed spectra). They are smoothed with the experimental spectral resolution.

The simulated transmitted spectrum [Fig. 2(a)] exhibits a shape similar to the measured spectrum with the characteristic transmission windows W1 and W2. The radiative burn through of the 5-μm-thick foil starts in the simulation as in the experiment at $t \approx 0$. Differences are present in the detailed temporal onset of the burn through, which occurred in the simulation somewhat faster than in the experiment. To achieve the agreement shown in Fig. 2(a) the calculated spectrum was taken at $t = 0.05$ ns, whereas the measured spectrum was obtained at $t = 0.2$ ns.

The calculated reemitted spectrum [Fig. 2(b)] shows similarly as the measured spectrum a strong fb continuum together with the dominant He α, Ly-α, and Ly-β lines, which are strongly opacity broadened in the optically thick layer. The level of the valleys between the lines [as well as the size of the transmission windows in Fig. 2(a)] is mainly determined by the overlapping line wings of the electron impact broadened lines. The simulated spectrally integrated flux (emitted along the normal of the carbon wall) is plotted in Fig. 3 (dashed line). It is slightly larger than the measured flux reemitted from carbon. The time-integrated value of the flux reemitted from carbon normalized to gold is $r_C/r_{Au} = 0.26$, which well agrees with the experimental value $r_C/r_{Au} = 0.23$.

Summarizing, radiative heating of CH plastic foils by intense thermal x rays has been studied experimentally at temperatures exceeding 100 eV. The investigation includes the temporally and spectrally resolved measurement of the reemitted radiation. The results agree well with numerical simulations which take into account the hydrodynamic motion of the foil and the radiative transport. For the latter an accurate modeling of the carbon opacity with the inclusion of electron impact broadened line transitions was essential. Thus we have confirmed experimentally a model which is appropriate to describe the reemission from radiatively heated low-Z matter. On this basis predictions can be made for other conditions like those occurring in ICF.

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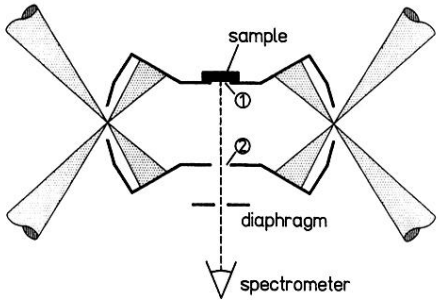

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