Radiation confinement in x-ray-heated cavities

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(Received 5 June 1990)

The confinement of high-temperature thermal radiation in x-ray-heated cavities was studied by relative measurements of the radiation temperature in "closed" and "open" cavities simultaneously heated by x rays generated in a common laser-heated cavity. The experimental observations provide direct evidence of radiation enhancement due to radiation confinement. We have developed a simple model based on the theory of the radiatively driven heat wave. The predictions of the model are in good agreement with the experimental results.

In recent times the confinement of the radiation field in cavities with reemitting walls has been the object of a vigorous research effort.[1] The intense thermal radiation created inside a closed-geometry target like a cavity is of interest because it has a number of applications, the most notable of which is the indirect-drive inertial confinement fusion.[2] Furthermore, the closed-geometry targets provide the possibility of studying in the laboratory a number of topics related to radiation hydrodynamics.[3] In previous experiments,[4-6] the radiation confinement in single gold cavities heated by laser beams was measured. However, these experiments suffer from two drawbacks that reduce the accuracy of the measurements and hinder their interpretation. First, the conclusions are based on difficult-to-perform absolute measurements of the enhanced radiation field. Second, the x-ray source (laser plasma) with which a cavity was heated was located inside the same cavity, which complicates the interpretation of the results.[6] To improve the accuracy of the measurements and have experimental conditions that are closer to the assumptions involved in the theoretical modeling, we have performed experiments with a more advanced target design.[7] This design enabled us to observe by relative measurements directly the radiation confinement in x-ray-heated cavities.

The target design can be seen in Figs. 1 and 2. It consists of three adjacent equidiameter gold cavities connected to each other through large openings. The laser energy is injected into the converter cavity in the middle, and it is partially converted into x rays. The upper and lower satellite cavities are heated by the x-ray flux from the converter cavity through the connecting openings. The difference between the two satellite cavities is that the upper is nearly closed, while the lower is more than half open. The advantages of the new target design should now be obvious. First, one can obtain, in a single shot, measurements of the x-ray flux enhancement by comparing the radiation intensity from the "closed" to that from the "open" satellite cavity, i.e., by relative measurements. Second, the phenomena associated with the laser-produced plasma are localized and isolated in the converter cavity, while the two satellite cavities are heated by x-ray radiation only.

Six beams of the Gekko-XII Nd:glass laser facility, in two bundles of three, irradiated the interior of the converter cavity wall. The laser spots were distributed symmetrically with respect to the two connecting openings so that the x-ray flux contribution from the laser plasma in the converter cavity to both satellite cavities would be strictly equivalent (see Fig. 1). The total energy injected into the converter cavity was $E_L = 2-2.7$ kJ of $\lambda = 0.35$ μm (3ω) laser light having a pulse duration [full width at half maximum (FWHM)] $\tau_L = 0.9$ ns. Each cavity possessed a diagnostic hole through which the corresponding x-ray flux was measured. Their diameter was appropriately scaled so that the resulting signals from all three holes fell within the dynamic range of the measuring instruments. In addition, their position was judiciously chosen to ensure that the radiation from the closed and open cavity emanates from completely symmetric wall elements with respect to the laser spots in the converter cavity and that the radiation from the converter cavity does not originate from an element heated by laser light. The details of the setup as a whole (cavity design, diagnostic hole location, viewing direction of the diagnostics, positioning of the laser-beam spots inside the converter cavity) were carefully thought out and designed so that there existed a physical separation and, therefore, noninterference between the laser-plasma-associated processes in the converter cavity and the x-ray heating process in the satellite cavities. For example, a simple ray-tracing computer code was employed to ensure that reflected light from the laser spots in the converter cavity does not traverse the connecting openings to the satellite cavities.

Two sizes of triple-cavity targets were used in these experiments; one having cavities with diameter of $D = 2$ mm

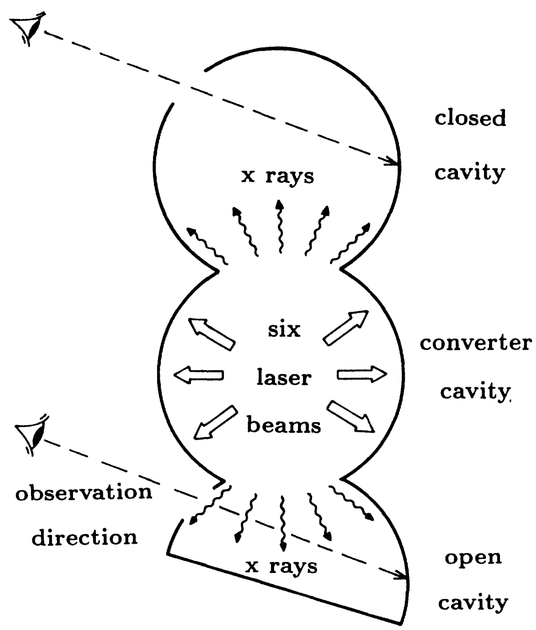

FIG. 1. Schematic diagram showing the method and sequence of heating the triple-cavity targets. The viewing direction of the diagnostic instruments is also indicated (the TGS and XRSC were positioned close to each other, pointing nearly at the same wall element).

and the other of $D=1$ mm. The two diagnostic holes on the closed and open cavity were 400 and 200 μm in diameter for the 2- and 1-mm cavities, respectively, while the diagnostic hole on the converter cavity was 100 μm in diameter for both size targets. The additional large openings on the wall of the lower cavity (see Fig. 2) serve the purpose of making the lower cavity as open as possible. On the side of the diagnostic hole, a part of the wall was kept as a radiation shield, and on the opposite side, a wall element exists which can be observed through the diagnostic hole. To characterize the "openness" of a particular cavity, we introduce the fractional hole area, which is defined as $n^{-1}=A_h/A_t=(A_t-A_w)/At_t$, where A_t is the total area occupied by wall elements and openings (holes) together, while A_w is the area occupied by the material wall and A_h by the holes only. Another important geometrical parameter is the fractional connecting area that characterizes the coupling between two cavities; it is defined as $n_c^{-1}=A_c/A_t$, where A_c is the common area of the connecting opening. Both sizes of the triple-cavity targets employed in these experiments had $n_{\rm conv}^{-1}=0.2$, $n_{\rm closed}^{-1}=0.08$, $n_{\rm open}^{-1}=0.68$, and $n_c^{-1}=0.067$ (i.e., the diameter of the connecting opening equal to the cavity radius). The wall was made out of approximately 10-μm-thick gold.

A spatially resolving transmission grating spectrometer (TGS) utilizing absolutely calibrated Kodak-101 x-ray film as detector[8] recorded the time-integrated spectrum from each diagnostic hole. A soft-x-ray streak camera[9] (XRSC) with an imaging slit (temporal resolution ~34 ps) measured simultaneously the spectrally integrated flux from all three diagnostic holes with spatial resolution. The information contained in the experimental data set delivered by these two instruments has been unfolded to obtain (a) the time-integrated spectrum from each diagnostic hole and (b) the corresponding temporal evolution of the radiation temperature of the spectrum. The XRSC data from a representative shot with a $D=2$ mm triple-cavity target are shown in Figs. 2 and 3. At the time of maximum emission, the converter cavity reaches a temperature of 137 eV. The satellite cavities, heated by x rays traversing the connecting opening, attain a temperature of 87 eV (closed cavity) and 75 eV (open cavity). The most significant result in these experiments, however, is the systematic difference in the temperature from the closed and open cavity which was observed in all experiments (total of six) and for both sizes of triple-cavity targets. Qualitatively, these results can be easily understood. The converter cavity is heated by the total x-ray flux delivered by the laser-produced plasma, while the two satellite cavities are heated only by a fraction of it, determined primarily by the size of the connecting openings. The reduced input power explains the lower temperatures in the satellite cavities. It is reasonable to as-

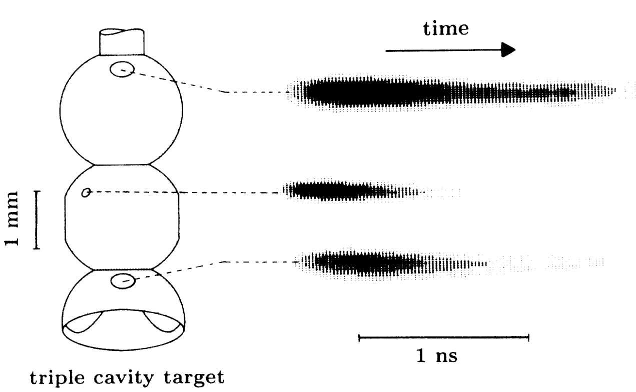

FIG. 2. X-ray streak camera record of the emission from the corresponding diagnostic hole of each cavity.

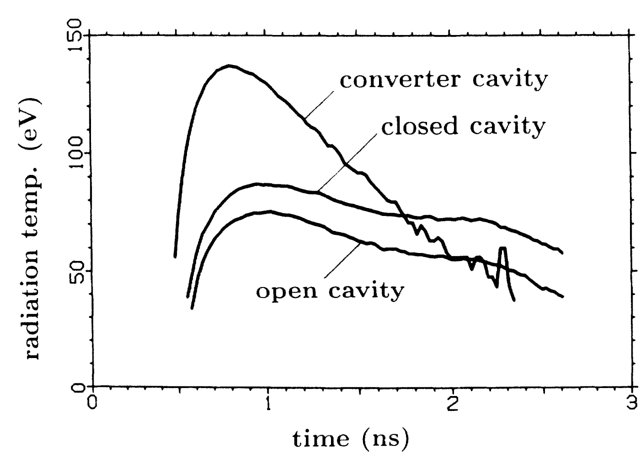

FIG. 3. Temporal evolution of the radiation temperature in a triple-cavity target with $D=2$ mm.

sume that the observed wall elements in the two satellite cavities are heated by the same x-ray flux from the converter cavity since the two openings are located symmetrically on the surface of the converter cavity and with respect to the laser-heated zone in it. The observed higher flux from the closed cavity compared to the flux from the open cavity can then be attributed only to the fact that in the closed cavity the observed wall element obtains additional heating by the radiation reemitted from the other wall elements of the same cavity. In the open cavity, because a large part of the wall has been cut away, this additional heating is largely absent. If there were not any confinement present in the closed satellite cavity, no temperature difference between the closed and open cavity would have been observed; the fact that the wall element in the closed cavity is heated to higher temperature provides direct evidence for radiation confinement by reemission in this cavity.

During the cooling phase, the temperature in the satellite cavities shows the occurrence of some reheating after ~ 1.2 ns. This is tentatively interpreted as an indication of the filling of the converter cavity with laser-produced plasma and the conservation of its kinetic energy into radiation.[6] This is not directly observed in the converter cavity. In addition, the temperature of the converter cavity falls apparently below the temperature in the satellite cavities, which is not reasonable. A possible explanation is that the small diagnostic hole of the converter cavity fills with cold plasma from its rim, which obstructs the observation of the hot cavity interior during the cooling phase.

It is possible to explain the main body of the observations associated with the heating phase by a semiquantitative model. In this model we have used the theoretical results developed for a single partially closed cavity[10] and extended them to describe the general case of two coupled cavities m and k. The following set of equations gives the values of the various fluxes that characterize the radiation field in the cavity m when this cavity is coupled to the cavity k.

$$S_{s,m}+S_{i,m}=S_{r,m}+S_{hw,m} , \tag{1}$$

$$S_{i,m}=(1-n_m^{-1})S_{r,m} , \tag{2}$$

$$S_{r,m}=ct^{\alpha}S_{hw,m}^{\beta} , \tag{3}$$

$$S_{s,m}=S_{ps,m}+(S_{ps,k}+S_{i,k})\Gamma_{km} . \tag{4}$$

The first equation expresses the energy balance at the vacuum-material interface of a wall element in the cavity. The sum of the total source flux that heats the cavity wall, $S_{s,m}$, and the flux $S_{i,m}$, consisting of contributions from all other wall elements in the cavity m to the total flux incident on the specific wall element under consideration, is balanced by the sum of the reemitted flux $S_{r,m}$ and the net heat flux $S_{hw,m}$ into the material wall element. For simplicity, we have assumed that each wall element behaves as an isotropic (Lambertian) emitter. For a spherical cavity this means that the emitted radiation falls uniformly on the cavity wall. Taking into account that holes do not emit, one obtains Eq. (2). The next equation [Eq. (3)] is a scaling law derived from the self-similar solution to the space- and time-dependent planar hydrodynamic equations with radiative heat conduction.[11] It gives the reemitted flux from a wall element as a function of time t and net heat flux $S_{hw,m}$ that drives the ablative heat wave. The material opacity has been incorporated in the value of the constant c, while the functional dependence of the opacity on temperature and density has been incorporated in the values of the exponents α and β (see Ref. 10). The Rosseland opacity for gold and its functional dependence on temperature and density have been calculated in the average ion approximation.[12]

The total source flux $S_{s,m}$ given by Eq. (4) comprises two parts. The first part, $S_{ps,m}$, is due to the primary x rays generated in the same cavity m. This term is absent if the cavity m is a satellite cavity. In the second part are the contributions of the cavity k to the source flux of cavity m. The first contribution, $S_{ps,k}$, is due to the primary x rays in the cavity k, and the second, $S_{i,k}$, is the incident flux consisting of photons reemitted in the cavity k and absorbed on the wall of cavity m. The coupling factor Γ_{km} is determined by the geometry of the two coupled cavities, and it can be easily estimated assuming that the radiation passing through the connecting opening of the two cavities is uniformly distributed on the inner area of the other cavity, except the portion A_c occupied by the common opening. In terms of the fractional connecting area, it is given by the relation $\Gamma_{km}=[n_{c,k}^{-1}/(1-n_{c,m}^{-1})](A_{t,k}/A_{t,m})$. Finally, the radiation temperature $T_{R,m}$ can be obtained from the reemitted flux using the relation $S_{r,m}=\sigma T_{R,m}^4$, where σ is the Stefan-Boltzmann constant.

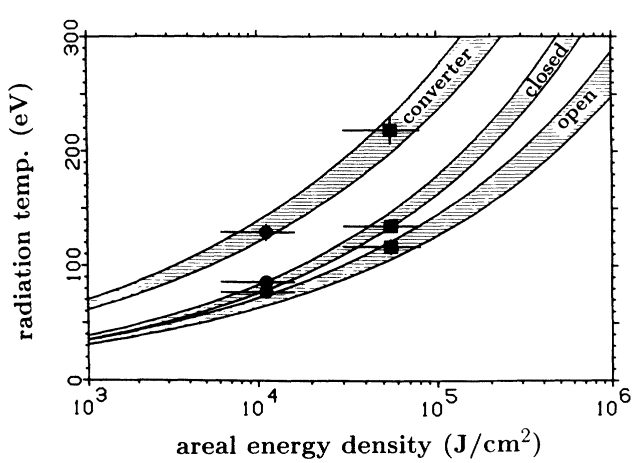

FIG. 4. Radiation temperature for each cavity in the triple-cavity system as a function of the areal energy density in the converter cavity. The hatched area represents the variation in the temperature when the heating period is increased from 0.4 ns (upper line) to 0.9 ns (lower line). The squares ($D=1$ mm) and the circles ($D=2$ mm) are the experimental points obtained in each case as the average over three shots. The error bars along the horizontal axis represent the uncertainty in the x-ray conversion efficiency, while the vertical error bars correspond to the statistical error as determined from the three shots.

Although the set of Eqs. (1)–(4) can be easily extended to describe a system of more than two interacting cavities, in practice, this is not necessary. For the conditions of our experiments, the coupling between the closed and open cavity and the "feedback" of the open cavity to the radiation field of the converter cavity can be neglected. For $S_{ps,\mathrm{closed}}=0$ (no primary source) and for $S_{ps,\mathrm{conv}}=\mathcal{E}_x^{\mathrm{av}}/t$, where $\mathcal{E}_x^{\mathrm{av}}=\eta_x E_L/\pi D^2$, the average areal energy density on the inner surface of the cavity is in the form of x rays, and t is the duration of the heating period (see following discussion), the system of Eqs. (1)–(4) is solved to obtain the fluxes for the closed and converter cavity of the triple-cavity target. Subsequently, for $S_{ps,\mathrm{open}}=0$, $S_{ps,\mathrm{conv}}=\mathcal{E}_x^{\mathrm{av}}/t$, and with the previously calculated value for $S_{i,\mathrm{conv}}$, the set of Eqs. (1)–(4) is again solved for the open cavity. For the conversion efficiency η_x of laser energy to x rays in the converter, we assumed $\approx 60\%$ for $\lambda=0.35$ μm as measured in experiments with planar targets.[13,14] The radiation field in all three cavities as a function of $\mathcal{E}_x^{\mathrm{av}}$ is given in Fig. 4.

The theory of the ablative heat wave[11] from which Eq. (3) is derived assumes that the cavity is heated for a period of time t by a constant source flux $S_{s,m}$. As a consequence, it is applicable only to the heating phase, during which the laser pulse is on, and not to the cooling phase, during which no source flux is present. A further inaccuracy in the comparison arises because the laser pulse approximates more a Gaussian than the flat top assumed in the theory. Therefore, the effective time of irradiation was treated as an open parameter. Variation of the duration of the heating period between 0.4 ns (shortest x-ray pulse observed from the converter cavity) and 0.9 ns (laser-pulse duration) leads to the hatched bands shown in Fig. 4. It is seen that the model predicts temperature values that are in good agreement with the experimentally obtained peak temperature values for all three cavities and for both size targets.

To conclude, although more work is required to understand the more subtle features of our experimental results, a first analysis has provided us with direct evidence for the importance of reemission in x-ray-heated cavities. This result confirms our interpretation of previous experiments with single-cavity targets.[5,6] The evidence for reemission from the present experiments is, however, more direct and obtained under conditions of pure x-ray heating.

This work was supported in part by the Commission of the European Communities in the framework of the Association Euratom-Max-Planck-Institut für Plasmaphysik and by the Monbusho International Scientific Research Program.

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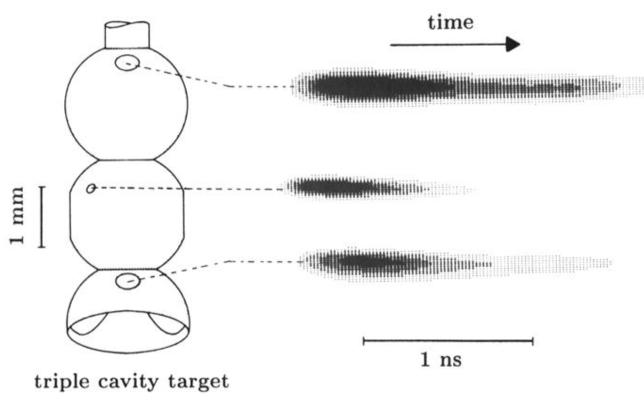

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