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LASER-INDUCED RADIATION HYDRODYNAMICS

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ABSTRACT

Short-wavelength laser radiation from high-power laser installations makes it possible to perform quantitative laboratory investigations of radiative heat transfer in hot, dense matter. In this report we concentrate on the generation and confinement of intense Planck radiation in laser-heated cavities. The results are relevant to indirect-drive inertial confinement fusion.

INTRODUCTION

By focusing the power of a pulsed laser beam on dense matter it is possible to achieve a state of very high energy density in the heated material. It may then occur that the energy received from the laser beam is partially re-emitted by the material as thermal radiation and radiative energy transport becomes the dominant transfer mechanism by which the energy is redistributed throughout the neighbouring material. In general the heated material will be set into motion as a result of the pressure increase due to the heating. With the help of high-power lasers it is thus possible to study various phenomena of radiation hydrodynamics in the laboratory and to extend our knowledge about the state of matter at very high densities and temperatures under conditions which approach those existing in the interior of stars (Sigel, 1991a).

At Max-Planck-Institut für Quantenoptik we are engaged in a research program devoted to the fundamentals of beam-matter interaction. As part of this program we are investigating problems of energy deposition of laser and heavy ion beams in matter, the radiative properties and equation of state of dense hot matter, phenomena of radiation hydrodynamics and x-ray lasers. In this talk which is given to a community whose main interest is in thermonuclear fusion, I shall concentrate on our studies of laser-induced radiation hydrodynamics which are of relevance for indirect-drive inertial confinement fusion (ICF). The most recent results reported below were obtained in collaboration with the Institute of Laser Engineering, Osaka University, Japan.

RADIATION CONFINEMENT

Basic to the phenomena to be discussed in this article is the interaction of intense radiation with a wall. It makes a fundamental difference, however, whether the wall is part of an open or closed configuration. In order to clarify this difference let us first ignore all detail. We assume that the wall receives a source flux S_s and, as result of heating, re-emits a flux S_r. If the wall is part of an open configuration, i.e. if, as shown in Fig. 1(a), a single wall is irradiated and the re-emitted radiation propagates freely away, it is clear from energy conservation that $S_r < S_s$ (we assume here a quasistationary situation). However, if the wall is part of a closed configuration (as in Fig. 1(b) where two walls forming a planar cavity are irradiated) the re-emitted flux may become much larger than the source flux, i.e. $S_r >> S_s$. The reason for this is obviously that the wall in this case receives not only the source flux but also the re-emitted flux from the opposite wall and part of this flux will also be re-emitted.

In a symmetric arrangement like Fig. 1(b) the fluxes of re-emitted photons directed towards the right and left are equal and may be called the circulating flux. Under quasistationary conditions S_r may be considered at a given time as being made up of photons which emanate from the source flux but have been once, twice, .. etc. been re-emitted by the walls. Summing up the contributions from the two walls one obtains

$$S_r = (r + r^2 + \ldots)S_s = \frac{r}{1-r}S_s = NS_s \qquad (1)$$

Thus, if the re-emission coefficient r approaches one, the circulating flux becomes much larger than the source flux.

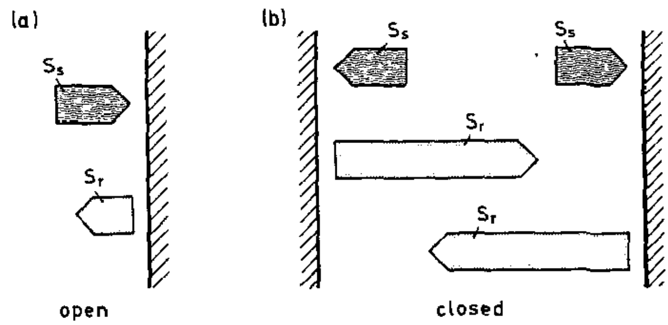

Fig. 1. Re-emission of radiation from a wall in an open (a) and closed (b) configuration.

The quantity $N = r/(1-r)$ represents the effective number of re-emissions and corresponds to the quality factor for radiation confinement in the cavity.

In indirect-drive laser fusion the inner wall of a cavity made of a high-Z material and containing a fusion capsule is heated by laser beams. It is important to note that the role of the cavity wall is not only to provide a target for the laser beams on which the laser energy is converted into incoherent soft x-rays. The cavity also provides a large circulating flux by re-emission of the primary x-rays from the cavity wall. The circulating flux drives the implosion of the fusion capsule and improves the uniformity of the radiating wall by redistributing the energy deposited by the laser beams. Multiple re-emission also enhances the efficiency of energy transfer to the fusion capsule (the consequences of radiation confinement have prevoiusly been demonstrated by the author in a model experiment, see (Sigel, 1987)). The closed geometry of a cavity is therefore of particular interest for fusion application.

THE PHYSICS OF CAVITY HEATING

A cross section through a laser heated cavity is shown in Fig. 2. The laser beams are injected through small holes as shown in the inset. Where a laser beam hits the cavity wall, a laser-produced plasma is formed which emits primary x-rays. The primary x-rays represent the source flux for the remainder of the inner wall of the cavity. As the cavity wall heats up it begins to re-emit the received energy as thermal radiation. At the same time diffusion of radiation into the deeper layers of the wall sets in and leads to the formation of a radiation heat wave. At the front of the propagating heat wave cold matter is heated, the energy being supplied by a net flow of heat into the wall. Assuming quasistationary conditions in an empty cavity with negligibly small holes, the net flow into the

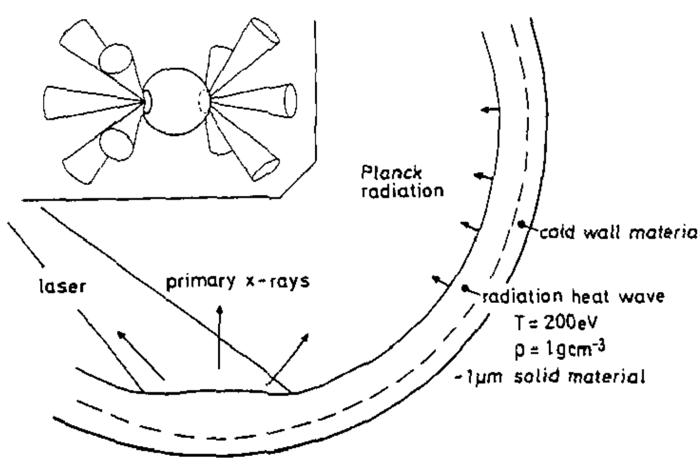

Fig. 2. Cross section through a laser heated cavity (schematic). The laser beams enter through holes as shown in the inset.

wall must be equal to the source flux falling onto the wall (the energy stored in the volume of the cavity may be neglected). The temperature of the hot material in the cavity wall is thus determined by the balance between the energy received from the source and the diffusive loss of radiation into the depth of the wall. The radiative loss decreases and the temperature increases with the opacity of the material; thus the wall is preferably made of a high-opacity, high-Z material, for instance gold.

A closer inspection of the radiative transfer into the wall shows that for times of interest for ICF (>100 ps) the heated material expands during the heating i.e. the heat wave is of the ablative type. Because the expanding material is still quite dense ($0.1 - 1$ gcm^{-3} at the sonic point) it may be assumed that radiation and matter are in complete thermodynamic equilibrium in the wave. In this limit the spectrum of the thermal radiation is a Planckian corresponding to the local temperature, and the radiative transfer into the wall may be calculated in the so-called conduction approximation. If one notes further that, due to the density difference between the expanding and the solid material the ablation is essentially the same as from a material of infinite density (i.e. the energy transfer to the shock wave which forms in the solid material may be neglected) it is possible to find a self-similar solution for the ablative heat wave (Pakula and Sigel, 1985, Pakula and Sigel, 1986, Sigel *et al.*, 1988). The profiles of temperature, density, and velocity for a solid of density ρ which initially occupied the half-space $x > 0$ are shown schematically in Fig. 3(a).

For a gold wall one obtains from the self-similar solution, using gold opacities calculated by Tsakiris and Eidmann, 1987, the following scaling laws:

$$T = 267\ \hat{S}_s^{4/13}\hat{t}^{2/13}\ \text{eV} \tag{2}$$

$$d_F = 3.3\ \hat{S}_s^{7/13}\hat{t}^{10/13}\ \mu\text{m} \tag{3}$$

Here T is the boundary temperature of the heat wave i.e. the temperature in the first Lagrangian cell of the wall. d_F is the penetration depth of the front of the heat wave into solid gold of density $\rho_0 = 19.3$ gcm^{-3}. $\hat{S}_s$ and $\hat{t}$ are in units of 10^{14} Wcm^{-2} and 10^{-9} s, respectively.

On a laser-irradiated area of the cavity wall the flow is modified by the heating due to laser light. It has been shown (Sigel *et al.*, 1990a, Eidmann *et al.*, 1990) that in this case the hot material may be subdivided into a re-emission zone and a conversion layer (see Fig. 3(b)). The laser light penetrates into the expanding material up to the critical density where the local plasma frequency equals the laser frequency (the critical electron density is given by $n_{ec} = 10^{21}/\lambda^2$ (μm) cm^{-3}). At densities at or slightly above the critical density a conversion layer forms where the plasma becomes strongly heated to temperatures of the order of $\sim$ 1keV. Due to the strong heating the plasma expands rapidly with a corresponding decrease in density. The conversion layer is optically thin to its own thermal radiation and radiates equally towards the cavity and the wall. The radiation directed towards the wall is partally re-emitted into the cavity by the re-emission zone. The re-emission zone corresponds essentially (except for the higher temperature due to the localized laser heating) to the radiative heat wave shown in Fig. 3(a).

The conversion layer is crucial for the laser approach to cavity heating. In this layer a competition takes place between the conversion of the absorbed laser energy into primary x-rays (the desired process) and the radiationless

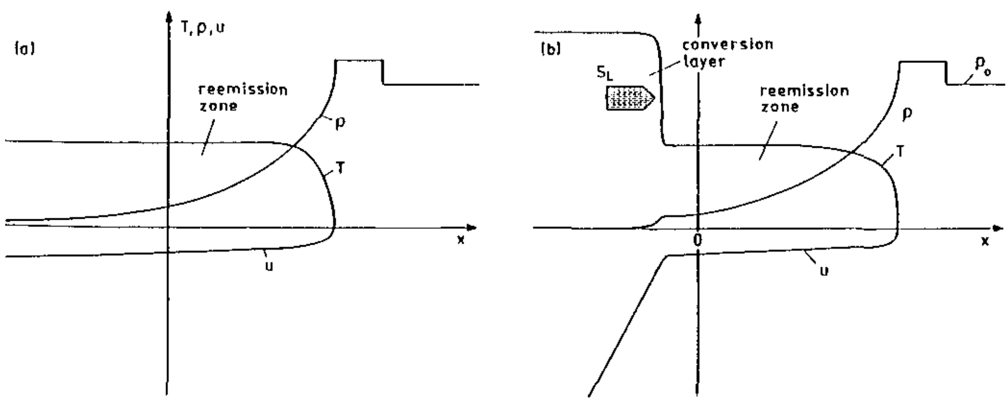

Fig. 3. Schematic representation of temperature (T), density (ρ), and velocity (u) profiles of the expanding wall plasma (for $t<0$ the wall material filled the half-space $x>0$ at constant density ρ_0). (a) The wall element is irradiated only by x-rays. (b) The wall element is irradiated in addition by laser light with a flux S_L.

loss of the energy as kinetic energy of the expanding plasma. Numerous investigations, both experimental and theoretical (for a review see Sigel, 1991a) have shown that a high conversion efficiency of order unity can be achieved only with short-wavelength laser light in the near UV part of the spectrum. In addition, short-wavelength laser light is efficiently absorbed in electron-ion collisions and the detrimental effects of laser-excited plasma instabilities, in particular the transfer of laser energy to suprathermal electrons, disappear or are at least greatly diminished. In most experiments performed today (including those reported below) therefore short wavelength laser light is applied.

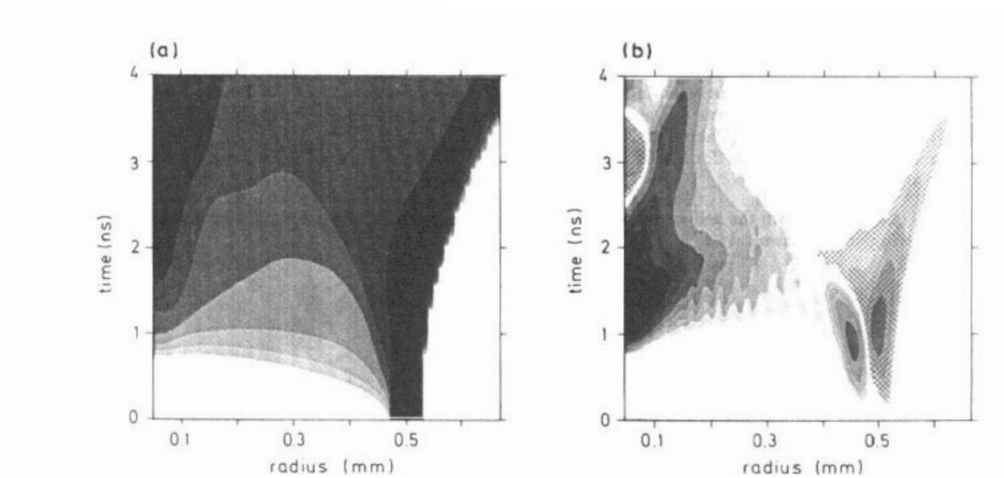

Fig. 4. Numerical simulation of the rapid plasma filling of a small cavity. (a) Contour plot of the density (logarithmic steps) (b) same for the divergence of the thermal radiation i.e. for the sources and sinks (dashed) of the radiation.

Up to now we have tacitly assumed that the flow of the heated material may be considered as planar. This is justified in large moderately heated cavities where the distance of plasma expansion during the irradiation time remains small compared to the cavity radius. However, if the cavity radius is decreased in order to increase the temperature for a given laser power, this may no longer be true. Fig. 4 shows results from a MULTI simulation (for a description of the MULTI code see Ramis *et al.*, 1988) for one of the smallest cavities heated during the present series of experiments (Massen, 1991). As may be seen from Fig. 4(a) the rapidly moving laser produced plasma implodes into the cavity forming a density spike in the center. Fig. 4(b) shows a plot of the divergence of the thermal radiation flux i.e. sources and sinks (dashed) of the radiation. Attached to the outward accelerated cavity wall is the re-emission zone which represents a sink for the radiation (dashed). The conversion layer, carried slowly towards the center by the flow, appears as a bright source of radiation. However, the imploding plasma in the center rapidly becomes a second source of radiation, in the case shown already during laser irradiation. The energy radiated by this source is provided by the kinetic energy of the imploding material which is converted into internal energy and radiation during the collapse. As a consequence the cavity is reheated and the maximum value of S_r is about 1.5 times larger than without the imploding plasma (this has been shown by calculations where the cavity diameter and corresponding the laser power were artificially enlarged). Although the effect may be less pronounced in experiments where the laser produced plasma originates in discrete laser-irradiated areas and does not have the perfect spherical symmetry of these 1-D spherical simulations, it is clear that cavity heating is more complicated in such cases. Another complication which may arise in strongly heated, small cavities is that the diagnostic holes in the cavity wall tend to fill with absorbing plasma ablated from the wall. This plasma could attenuate the re-emitted radiation from the wall elements which are under observation through the diagnostic holes.

EXPERIMENTS

Experiments were recently performed by a MPQ/ILE collaboration at the Gekko XII Nd: glass laser (Sigel *et al.*, *1991b)* in Osaka. An essential feature of these new experiments is the use of short-wavelength ($\lambda = 0.35\mu$m) laser radiation. Compared to previous experiments of this collaboration with $\lambda = 0.53\mu$m laser radiation (Mochizuki *et al.*, 1987, Sigel, 1987) one expects higher temperatures for a given energy input due to improved x-ray conversion efficiency of laser light into x-rays.

Ten laser beams injected up to 5 kJ laser energy into the cavities with a pulse duration of 0.8 - 0.9 ns. Different types of cavities were used as shown in Fig. 5. They were made of gold with a wall thickness of 10 μm . The standard cavities of type A (3, 2, or 1mm diameter) have a hole carrying a foil (f), a reference hole (r), a hole for the measurement of the brightness temperature in the cavity (t), and two laser holes (l). The ten laser beams incident, as shown in the inset of Fig. 2, in two bundles of five at an angle of 50 degrees with respect to the axis connecting the two opposite laser holes (only one of them is visible in Fig. 5), heat the inner surface of the cavity on the equator between the laser holes. The cavities type B (2 or 1 mm diameter) consist of three cavities coupled by the transfer of radiative energy through connecting holes. Only the middle cavity is heated by laser light. The upper cavity is nearly closed whereas the lower cavity has large holes (h). It is thus possible to study the effect of holes on radiation confinement by relative measurements between the closed and open cavities which are both heated by x-rays only. In addition the upper, x-ray heated cavity provides the possibility of foil burn-through measurements (see below) with the help of holes f and r. Cavity C differs from A in the way the laserlight is coupled to the cavity. Behind the laser holes the beams are absorbed inside five cones. The primary x-rays from the laser-produced plasma formed in the cones heat the wall surrounding the laser hole. The central part of the cavity which carries the diagnostic holes is heated only by re-emitted x-rays propagating through the gaps between the cones. Results obtained with cavity C will not be discussed here; they have been described by Nishimura *et al.*, 1991.

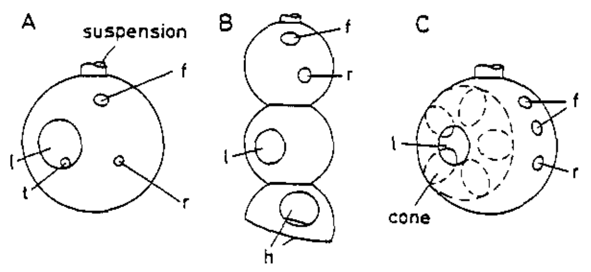

Fig. 5. Cavities of type A-C used in the experiments. Small letters denote the holes carrying a foil (f), the open reference holes (r), the laser holes (l), the holes for temperature measurement (t), and additional holes (h) in the open cavities.

Absolute, but time-integrated measurements of the spectrum of the radiation emitted by the diagnostic holes were made with transmission grating spectrometers (TGS's) and absolutely calibrated Kodak 101-01 film. The temporal variation of the radiation was measured with an x-ray streak camera (XRSC). By combining the two measurements it is possible to obtain the time-integrated spectral intensity of the radiation as well as the brightness temperature in the cavity as a function of time. These lasers are shown in Fig. 6(a) and (b) for a 1mm cavity. The spectral intensity is in approximate agreement with a best fit Planckian with a temperature of 230 eV. The deviations at low photon energies are tentatively attributed to the very soft radiation emitted during the cooling phase.

In the experiments with triple-cavity targets of type B, described in detail by Tsakiris *et al.*, 1990, the middle (converter) cavity was heated by 6 laser beams (see Fig. 7(a)). The upper (closed) and lower (open) cavity were heated by the x-rays from the converter cavity which propagate through the large connecting holes. Great care was taken in the design of the target with respect to the positioning of the laser beams and the location of the diagnostic holes in order to ensure that the wall elements observed through the diagnostic holes receive the same amount of x-rays from the converter cavity. Nevertheless it is expected that the observed wall element in the upper (closed) cavity reaches a higher temperature because in the closed cavity it receives re-emitted radiation from a

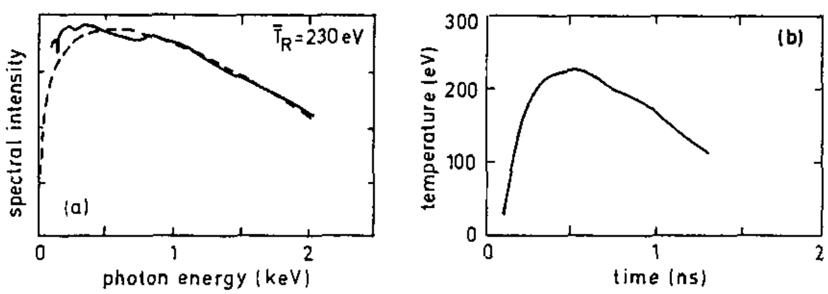

Fig. 6. Time integrated soft x-ray spectrum (a) and brightness temperature versus time (b) measured in an experiment with a 1 mm diameter cavity of type A. The dashed line in (a) represents a best fit Planckian spectrum.

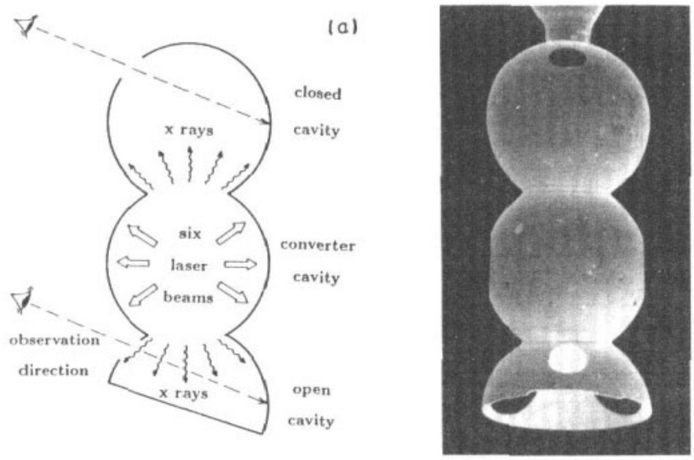

Fig. 7. (a) Schematic diagram showing the method and sequence of heating the triple-cavity targets. The viewing direction of the diagnostic instruments is also indicated (the TGS and XRSC were positioned close to each other, pointing nearly at the same wall element). (b) SEM photograph of the actual cavity.

larger area than in the open cavity. Fig. 7(b) shows a photograph of the actual cavity from a direction where the two diagnostic holes of equal diameter in the upper and lower cavity and a third one in the converter cavity can be seen.

The three diagnostic holes were imaged with spatial resolution onto the photocathode of an XRSC; in this way the temporal evolution of the radiation field could be recorded simultaneously for the three cavities (see Fig. 8(a)). In addition the time-integrated spectrum emitted by each diagnostic hole was measured absolutely with a TGS. Fig. 8(b) shows the temporal variation of the temperature in the three cavities, derived from these measurements. The highest temperature is obtained in the laser-heated converter cavity. In all experiments with this type of targets the temperature in the open cavity was always lower than in the closed cavity as expected. An interesting detail is the observation that in the two satellite cavities ~1.2 ns after the first temperature maximum the temperature shows another flat maximum. Simulations of the type shown in Fig. 4 suggest that this observation should be attributed to a reheating of the converter cavity by the imploding plasma which affects also the satellite cavities via radiative transfer through the connecting holes. The apparently rapid decrease of the temperature in the converter cavity and the lack of evidence for reheating in the temperature signal of this cavity are taken as indications that the diagnostic hole in this cavity was too small (100 μm diameter as compared to 400 μm diameter for the other two cavities) and plasma filling from the edges of the hole possibly lead to strong attenuation of the radiation from the interior of the cavity during the cooling phase. Attenuation of the radiation in the diagnostic holes certainly needs further attention in the future.

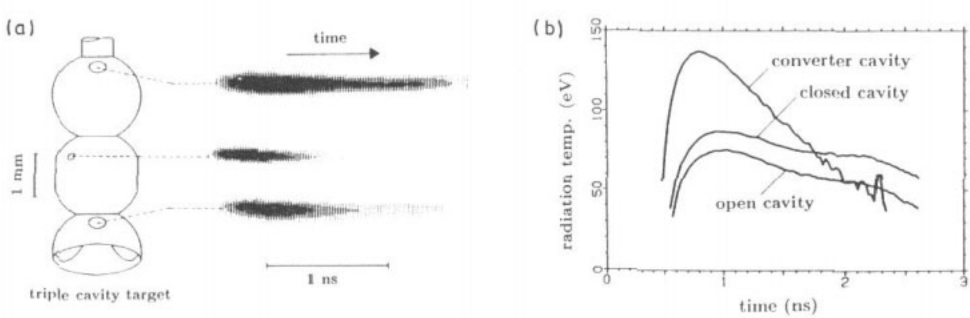

Fig. 8. (a) X-ray streak camera record of the emission from the corresponding diagnostic hole of each cavity. (b) Temporal evolution of the radiation temperature in a triple-cavity target with 2 mm diameter.

It is possible to develop a simple model for the triple cavity target on the basis of the self-similar solution of the ablative heat wave, taking into account the proper boundary conditions for cavities with holes and the energy exchange between the radiatively coupled cavities (Tsakiris *et al.*, 1990). The good agreement between this model and the experiments represents a rather direct confirmation of radiation confinement because the satellite cavities are only x-ray heated and do not suffer from the complications rising from the presence of laser light.

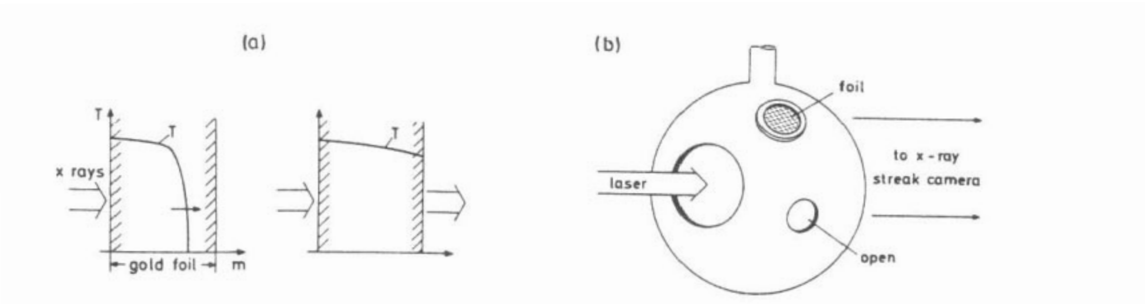

Fig. 9. (a) Left: Propagation of an x-ray-driven radiation heat wave through a thin gold foil; m is the mass coordinate. Right: After arrival of the wave the rear side of the foil emits intense thermal radiation. (b) Schematic representation of a laser-heated cavity with a thin gold foil mounted on one hole and with an open reference hole.

By now laser-heated cavities have reached a state of perfection where they can be used as drivers for experiments devoted to the study of phenomena of radiation hydrodynamics and the state of matter at high density and temperature. Besides the experiments with the triple cavity targets we have performed an investigation of the radiation heat wave which penetrates the wall of the cavity and provides radiation confinement (Sigel *et al.*, 1990b). The principle of the experiment is shown in Fig. 9(a). Part of the cavity wall is made of a thin gold foil into which the heat wave is driven by the cavity radiation. At the moment when the steep front of the heat wave arrives at the outer surface of the foil, a sharp onset of thermal emission is expected. Thus the transit time of the heat wave can be measured and compared with theoretical expectations. Experimentally the thin foil is mounted on a hole in the cavity wall; a second hole serves as a reference hole (Fig. 9(b)). Monochromatic (observed wavelength 60 Å), spatially resolved images are formed on the photocathode of an XRSC (except for the use of monochromatic radiation the technique is similar to that applied to obtain the results shown in Fig. 8(a)). Two traces are registered on the screen of the XRSC. The one associated with the reference hole records the time variation of the radiation falling from the interior of the cavity onto the wall (including the foil) and the other the radiation from the outer side of the foil. The result of such an experiment is shown in Fig. 10(A). It is seen that the foil starts radiating with

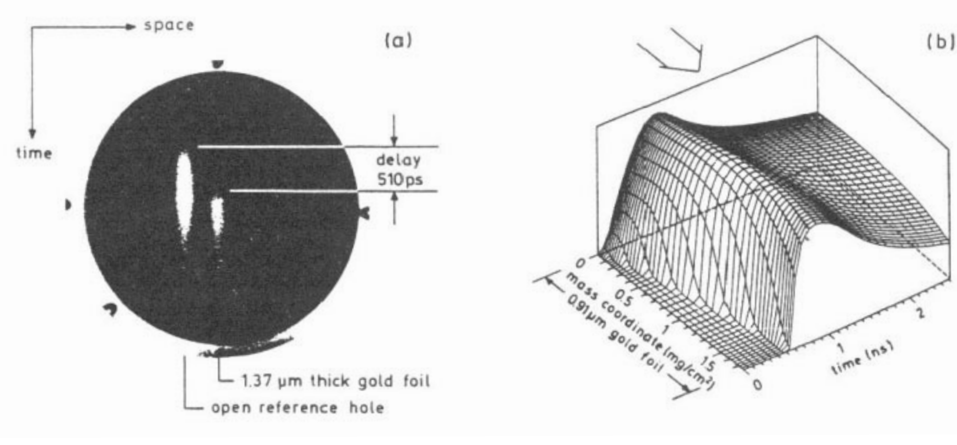

Fig.10. (a) Screen of the x-ray streak camera showing signals from the gold foil and the open reference hole. Observed wavelength 60Å. Cavity temperature 230 eV. Fiducial marks are seen at the periphery of the screen. (b) Evolution of the flux of outward-directed photons in the wavelength interval 55-65 Å inside the heated foil from a MULTI simulation of the experiment shown in (a). The vertical scale is linear.

a sharp onset after a delay of 510 ps. Similar results were obtained with cavities of type A, B and C (for target B the foil was mounted on the upper, closed cavity) for all the different cavity sizes. The measured delay times are in good agreement with eq. (3), i.e. the self-similar heat wave solution, as well as with numerical simulations. As an example of the simulations Fig. 10(b) shows the calculated radiation flux in the interval 55-60 Å as it penetrates into the foil. The calculated delay of 500 ps is in good agreement with the corresponding experiment (Fig. 10(a)).

A summary of the results related to the cavity temperature and confinement and illustrating the wide range of experimental conditions is shown in Fig. 11 (Sigel *et al.*, 1991b). The spectrally integrated reemitted flux S_r measured at the time of maximum emission, is plotted versus the incident laser flux S_L, calculated by dividing the incident laser energy by the pulse duration and the surface area of a sphere with the target diameter. The results shown in Fig. 11 were obtained with the most frequently used cavity A with diameters of 3, 2, and 1 mm (a more detailed account of the results, including those obtained with the other types of cavities, has been given by Nishimura *et al.*, 1991) . In the smallest cavities we reached a temperature of 240 eV, corresponding to $S_r = 3.4 \times 10^{14}$ Wcm^{-2}.

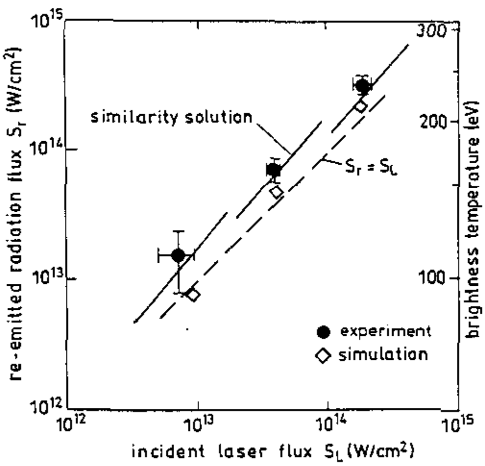

Fig.11. Re-emitted flux S_r and corresponding brightness temperature measured with cavities of type A of 3, 2, and 1 mm diameter (from left to right). For the evaluation of the similarity solution the fractional hole area n^{-1} for each cavity size and the conversion efficiency given in the text were taken into account.

The confinement effect of the wall becomes obvious from the observation that $S_r > S_L$ in all experiments i.e. the observed wall element re-emits more power in the form of thermal radiation than it receives from the laser. The additional heating is provided by radiation received from other wall elements in the cavity. Such a net enhancement (i.e. $S_r/S_L > 1$) could not be achieved previously with $\lambda = 0.53\ \mu$m laser light and shorter (300 ps) pulses (Mochizuki *et al.*, 1987, Sigel, 1987). In order to compare the experimental results with the similarity model, the conversion efficiency of laser light into primary x-rays $\eta_x = S_s/S_L$ should be taken into account. Assuming values of η_x of 0.8, 0.7 and 0.5 for the 3, 2, and 1mm cavities, respectively, as suggested by measurements of the conversion efficiency in open geometry (see e.g. Goldstone *et al.*, 1987) , the similarity model is indeed found to be in good agreement with the experiments (see Fig. 11). The reemission coefficient r and the number of re-emissions $N = r/(1-r)$ can be obtained from the relation

$$S_r = \frac{\eta_x S_L}{N^{-1} + n^{-1}} \tag{4}$$

using the measured values for $S_r$and η_x (the latter from experiments in open geometry as mentioned above). Eq. (4) may be derived in a similar manner as eq. (1) but taking the additional losses through holes with a fractional hole area n^{-1} into account ((Sigel *et al.*, 1988)). Using the measured values for $S_r$and $S_L$one obtains, for example, for the 1 mm cavity ($n^{-1} = 0.09$) from eq. (3) N=5.3 or r=0.85.

The experiments were also simulated in the multigroup diffusion approximation using the MULTI (Ramis *et al.*, 1988) and ILESTA (Takabe *et al.*, 1988) codes. As shown in Fig. 11 the results are in approximate agreement with the experiment with a tendency for the measured values of S_r to be slightly higher than those calculated.

INDIRECT-DRIVE LASER FUSION

The high radiation temperatures of >200 eV achieved in laser-heated cavities fall already into the parameter range of interest for indirect-drive inertial confinement fusion (ICF).

Fig. 12 shows a target configuration containing a fusion capsule which is being used at the Institute of Laser Engineering, Osaka University, to study indirect-drive ICF (Kato *et al.*, 1991). It consists of a gold cylinder which is open at both ends for injection of two bundles of 5 laser beams each (Fig. 12(a)). The fusion capsule is located in the center of the cylinder, a slit allowing the observation of the implosion (Fig. 12(b)). The advantage of this cylindrical cavity is its mechanical simplicity and the possibility to study the influence of the irradiation geometry on the symmetry of the implosion. Thus, by varying the distance from the fusion capsule to the annular zones where the laser beams hit the cylinder wall, it was possible to vary the shape of the imploding core. Up to now a ρR product of $10^{-2}\mathrm{gcm}^{-2}$, an ion temperature of 4 keV and a neutron yield of 1.6×10^9 have been obtained. Similar values had been reported previously by LLNL (Kilkenny *et al.*, 1989), but the target configuration was not revealed.

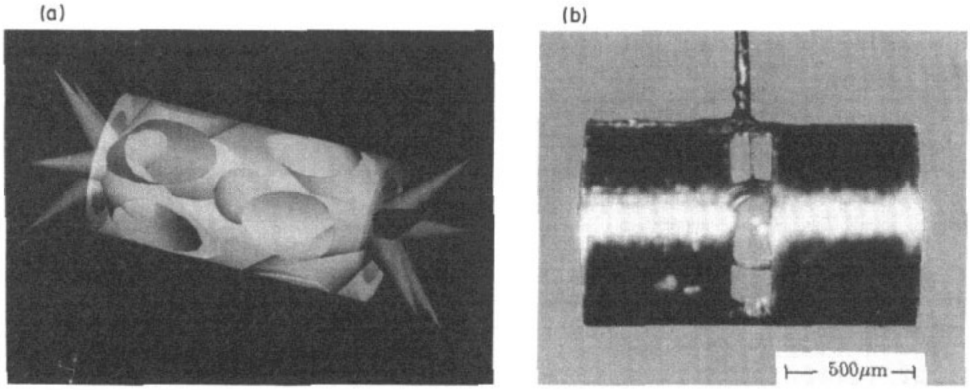

Fig.12. (a) A schematic view of a radiation-driven cylindrical cannonball target irradiated by 10 laser beams. The cavity is shown as a transparent cylinder. (b) Photograph of the target shown in (a).

Much of the progress in this field is due to the successful generation of short wavelength radiation which has largely eliminated problems connected with nonlinear laser-plasma interaction, in particular the generation of fast electrons (the absence of such problems in the shallower density gradients produced by laser pulses of much higher energy and longer pulse duration has still to be confirmed). A general difficulty lies in the fact that with the energies envisaged for laboratory ICF only modest re-emission factors can be achieved in the cavity. Hence a uniform and at the same time efficient irradiation of the fusion capsule is not easily accomplished. However, there is now increasing confidence that ignition and moderate gain can be achieved with about 2 Megajoules of short wavelength laser light (Storm *et al.*, 1991).

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