X-ray generation in a cavity heated by 1.3- or 0.44-μm laser light. III. Comparison of the experimental results with theoretical predictions for x-ray confinement

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Radiation confinement in laser-heated gold cavities is analyzed on the basis of self-similar solutions of the hydrodynamic equations. The analysis is extended to include radiation losses through holes in the cavity. The possibility that a conversion layer on the inner wall of the cavity contributes to the measured radiation is also taken into account. The comparison with experiments performed at laser wavelengths of 0.44 and 1.3 μm with the Asterix iodine laser shows reasonable agreement with the theoretical predictions. The major difficulty in the comparison is the lack of detailed information about the conversion of laser light into x rays, especially in the 1.3-μm experiments.

I. INTRODUCTION

If the energy of a powerful pulsed laser beam is converted into x rays in a nearly closed cavity of high-Z material, the x rays will be reabsorbed by the wall of the cavity and heat it. When the temperature of the wall begins to exceed 10^5-10^6 K it will itself become an intense radiator and eventually determine the radiation field in the cavity. For applications it is important that at such high temperatures multiple reemissions of the radiation in the cavity can lead to an isotropic radiation field even if the irradiation of the cavity by the laser is not uniform. Limits exist, however, for the temperature which is established in a balance between gain and loss of energy. In a closed, empty cavity the main loss is caused by the diffusion of radiation into the depth of the wall.[1]

X-ray generation in a cavity by laser light may be considered as a two-step process. In the first step the laser light is converted into primary x rays which deposit their energy on the wall of the cavity. In the second step the energy is partially reemitted by the wall and supports an equilibrium radiation field in the cavity. In this investigation the main emphasis is on the second step, i.e., on the confinement of the radiation by the cavity.

The reemission of thermal radiation by the wall takes place in very dense material where the assumption of local thermodynamic equilibrium between radiation and matter can be made. As we have shown in our previous study[1] this simplifies the analysis of the confinement problem considerably. In this case one deals with blackbody radiation in the cavity which is characterized by the temperature alone and does not depend directly on the atomic properties of the wall nor on the physical nature of the source. The radiative loss into the wall can be treated in the approximation of radiation heat conduction on the basis of self-similar solutions to the hydrodynamic equations.[2]

In this study we use our previous results to analyze the radiation confinement obtained in laser-heating experiments of small gold cavities with the Asterix iodine laser. The experiments, performed at two laser wavelengths of 1.3 and 0.44 μm with an input up to an average absorbed laser flux of about 5×10^{13} W cm^{-2} into the cavity, were described in detail in papers I (Ref. 3) and II (Ref. 4) of this investigation.

In our analysis we shall consider two scenarios, (a) and (b), which are shown in Figs. 1(a) and 1(b), respectively. In scenario (a), called the x-ray-heated cavity in the following, the primary x rays from a restricted laser-heated area heat the wall of the cavity. In scenario (b), called the cavity with a conversion layer, it is assumed that the conversion into x rays takes place all over the inner surface of the cavity.

The single-beam experiments which we shall analyze belong in principle to scenario (a). The measurements were made in such a manner that one observes through a small diagnostic hole only the x-ray heated wall, but not the very hot, laser-generated plasma. The interest in scenario (b) is in part motivated by the circumstance that in the experiments with 1.3-μm laser light a clear spatial separation between the generation and deposition of the x rays does apparently not exist. This raises the question as to the contribution of the conversion layer to the observed radiation. A more general interest in scenario (b), extending beyond the scope of this paper, is due to the fact that it corresponds approximately to the situation in multibeam irradiations of a cavity.

In Sec. II we shall briefly summarize our previous analysis of the x-ray-heated cavity [scenario (a)] and extend it to include the effects of holes. In Sec. III the cavity with a conversion layer [scenario (b)] is considered. In Sec. IV we shall compare the experimental results with the theoretical predictions.

II. X-RAY-HEATED CAVITY

A. Closed cavity

In scenario (a) the cavity wall is heated by primary x rays from a restricted laser-irradiated area. It is assumed that the x rays deposit their energy so deep in the hot

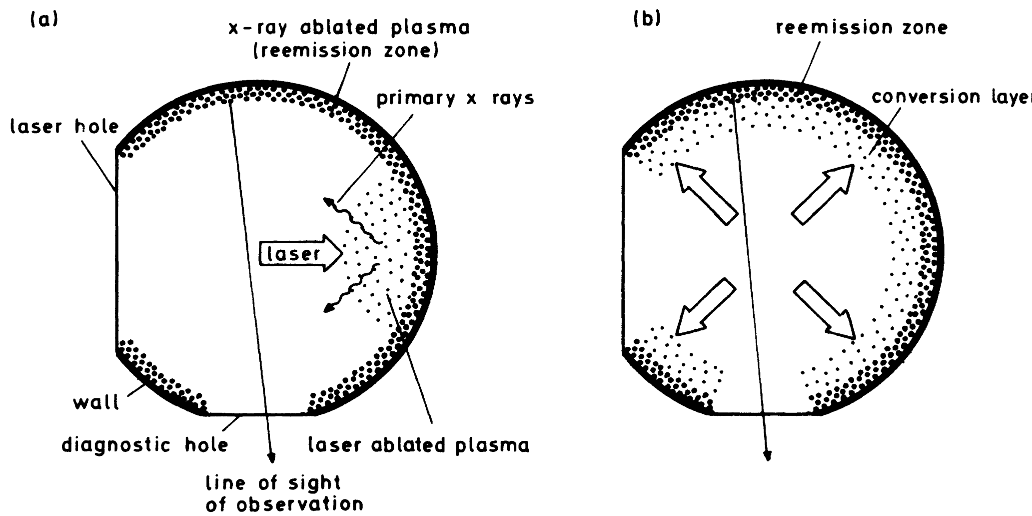

FIG. 1. Two scenarios (a) and (b) considered for cavity heating with a laser. (a) The absorbed laser energy is partially converted into primary x rays in a laser ablated plasma at the back wall of the cavity. X-ray heating of the wall leads to the formation of an x-ray ablated plasma which reemits part of the energy in the form of blackbody radiation. (b) Laser ablated plasma (conversion layer) is generated all over the inner surface of the cavity. An observer receives primary x rays from the conversion layer in addition to the blackbody radiation from the x-ray ablated plasma (reemission zone).

wall that the signature of the deposition process is not felt at the surface where the energy is reemitted as blackbody radiation. Within the conduction approximation the deposition of energy is taken into account only in a global manner as a boundary condition for the radiative heat flux into the wall. For a closed cavity the proper boundary condition is a given heat flux into the wall, called the source flux for the ablative heat wave in the following, which may be obtained from the absorbed laser power, the conversion efficiency into primary x rays, and the inner surface area of the cavity.

The diffusion of radiation into the wall of the cavity leads to the formation of a nonlinear heat wave. Simultaneously expansion of the heated material sets in. The space- and time-dependent planar hydrodynamic equations with radiative heat conduction admit a self-similar solution of the problem, the ablative heat wave.[2] The temperature and density profile are shown schematically in Fig. 2 over the mass coordinate m. As was verified by numerical calculations[5] the shock wave generated at the front of the wave is not essential for the radiative loss (at least not for the parameter range applicable to our experiments) and can be eliminated from the problem by the assumption of infinite solid density. For the boundary condition of a given heat flux into the wave, the temperature at the vacuum-material interface (i.e., at $m=0$) is, in the notation of Ref. 2, given by

$$T=K^{1/\delta}[a^{-2}(S_v/\tilde{S}_v)^{2(\mu+1)}t^2]^{1/\delta(2\lambda+3\mu+1)} . \quad (1)$$

S_v (the index v relates to the vacuum-material interface) is the given net heat flux into the wave, t is time. The constant K and the exponent δ relate to the expression for the specific internal energy e,

$$e=\frac{KT^\delta}{(\gamma-1)} ,$$

where γ is the adiabatic index. The constant a is determined by the Rosseland mean-free-path l_R. It is assumed to be given in the form

$$l_R=A_l T^j v^{\mu'} ,$$

where A_l is a constant and v is the specific volume.

The exponents appearing in Eq. (1) and in the expression for l_R and e are related by $\lambda=(\nu+1-\delta)/\delta$, $\nu=j+3$, $\mu=\mu'$. The constant a is given by $a=(\frac{16}{3})\sigma A_l/(\delta K^{(\nu+1)/\delta})$, where σ is the Stefan-Boltzmann constant.

As in Ref. 2 we assume in the following for gold $K=7.4\times10^3$ cm^2 s^{-2} K$^{-3/2}$ and $\delta=\frac{3}{2}$. l_R is derived either from the opacity (defined as $v^{-1}l_R$) of gold[6] as calculated in a hydrogenic average ion model or from the maximum opacity of Bernstein and Dyson[7] (in both cases we assume for the ratio of the nuclear charge Z to the atomic number A the value 0.4). For gold one has

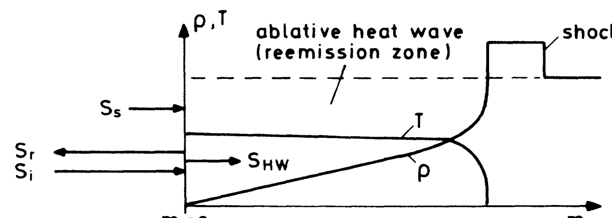

FIG. 2. Temperature and density profile of the ablative heat wave vs the mass coordinate m. The dashed line shows the initial density profile. S_s is the source flux, S_r the reemitted flux, S_i the incident flux received from the ablative heat wave existing on the opposite wall, and S_{HW} the net heat flux into the wave.

$$A_l = 2.76\times 10^{-10}\ \mathrm{K}^{-1}\,\mathrm{g\,cm}^{-2}\ ,$$

and for a material with maximum opacity,

$$A_l = 3.46\times 10^{-11}\ \mathrm{K}^{-1}\,\mathrm{g\,cm}^{-2}\ ,$$

with $(j,\mu')=(1,1)$ in both cases. For an adiabatic index of $\gamma=\frac{5}{4}$ and a temporally constant flux the constant $\widetilde{S}_v$ has the value[2] of 1.33.

For a closed cavity the net heat flux S_v into the ablative heat wave is equal to what we call the source flux S_s (compare Sec. II B). Equation (1) yields then for these two cases

$$T=\begin{cases} 25.5 S_s^{4/13} t^{2/13} & \text{(gold opacity)} \quad (2a)\\ 35 S_s^{4/13} t^{2/13} & \text{(maximum opacity)}\ , \quad (2b)\end{cases}$$

where T is in degrees Kelvin, S_s in $\mathrm{erg\,cm^{-2}\,s^{-1}}$, and t is in seconds.

For the conditions of the present experiments the optical thickness of the ablative heat wave is only of order unity and hence the flux reemitted by the wave may be less than predicted by these formulas which assume equilibrium between radiation and matter (in equilibrium the matter and radiation temperature are equal, the spectral distribution of the radiation is a Planckian, and the reemitted flux has the value σT^4). As we have shown earlier[8] the spectrum of the reemitted radiation can be obtained in an approximate manner by solving the radiation-transfer equation for the density and temperature profiles of the heat wave. These calculations give a somewhat reduced brightness temperature[9] (see Fig. 1 in Ref. 9). However, this reduction may not be real because the calculations are not self-consistent. Until more realistic calculations are available we shall therefore use the analytical expression (2a) in our analysis of experiments with gold cavities.

B. Cavity with holes

The results summarized in Sec. II A were obtained for a completely closed cavity. We shall now consider a cavity with holes through which radiation can escape. The losses of radiation through holes will reduce the radiant energy flux in addition to the effect caused by the losses into the wall.

We call the source flux on the wall S_s, the x-ray flux falling from the interior of the cavity on the wall S_i, the reemitted flux of x rays S_r, and the net heat flux into the wall S_{HW} (instead of S_v, we follow here the notation of Ref. 1). We characterize the radiative properties of the wall by the quantity

$$N=\frac{S_r}{S_{HW}}\ .$$

It can be verified that N is a wall property by expressing it through the reemission coefficient r, defined by

$$r=\frac{S_r}{S_i+S_s}\ .$$

By using the energy balance at the vacuum-material interface

$$S_s+S_i=S_r+S_{HW}\ ,$$

it is seen that r and N are connected through the relations

$$r=\frac{N}{N+1},\quad N=\frac{r}{1-r}\ .$$

Let us now consider a cavity with holes. We assume that the cavity is uniformly irradiated by the source and that the holes are small and uniformly distributed in an average sense such that the isotropy of the radiation field in the cavity is not disturbed. The holes occupy a fraction n^{-1} of the total wall area (including holes). If we average over the material parts of the wall and the holes, energy conservation yields

$$S_s+S_i=(S_r+S_{HW})(1-n^{-1})+(S_s+S_i)n^{-1}\ . \quad (3)$$

That is, from the total incident flux S_s+S_i, a fraction $1-n^{-1}$ is intercepted by the wall and either reemitted or lost into the wall: a fraction n^{-1}, i.e., the rest, is transmitted by the holes towards the outside. Because with our assumptions no energy transport takes place across the cavity in the form of x rays, we have $S_i=(1-n^{-1})S_r$ and Eq. (3) becomes

$$S_s=S_{HW}+n^{-1}S_r\ . \quad (4)$$

It is seen that for $n^{-1}=0$ one has $S_{HW}=S_s$. This is the boundary condition we have used in Sec. II A for a closed cavity (with the notation S_v instead of S_{HW}). Using the definition of N one obtains

$$S_r=\frac{1}{N^{-1}+n^{-1}}S_s\ . \quad (5)$$

Let us come back for a moment to the closed cavity (i.e., $n^{-1}=0$) and write this equation in the form

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

It is seen that N may be called the flux enhancement factor or, by analogy to a microwave cavity, the quality factor for the confinement of incoherent radiation. It becomes large as r approaches unity. The reemitted flux S_r which could be called the circulating flux for a closed cavity (where $S_r=S_i$) is made up of reemitted photons which are effectively N-times reemitted in the cavity.

In a cavity with holes [see Eq. (5)], N is replaced by the factor $(N^{-1}+n^{-1})^{-1}$ which could be called the effective quality factor in the presence of holes. The term N^{-1} stands for the wall losses and n^{-1} for the losses through the holes. Both types of losses are equally important if $n^{-1}=N^{-1}$.

If a cavity with holes is heated, the relative importance of the wall losses and the losses through the holes changes with time. Initially when the wall temperature and S_r are still small, the wall losses dominate and the presence of holes is not important. In fact, it is seen from Eq. (4) that for $S_{HW}\gg n^{-1}S_r$ we have $S_s\cong S_{HW}$ i.e., the boundary condition of a closed cavity. For $t\to\infty$, however, the walls become highly reemitting and the power supplied by the source is radiated through the holes (here we ignore effects of cavity filling[1]). In this limit we have

$S_{HW} \ll n^{-1}S_r$ and hence from Eq. (4) $S_r \cong S_s/n^{-1}$ or $T \cong T_\infty = (S_s/\sigma n^{-1})^{1/4}$.

In practice, one is interested to assess the importance of holes for given conditions, i.e., at a given time for a given source flux S_s and a fractional hole area n^{-1}. It is, in fact, possible to find an approximate relation which describes the evolution of S_r with time in a cavity with holes. This relation may be obtained by eliminating S_{HW} between Eq. (4) and Eq. (1) [or the specialized equations (2a) or (2b)].

At this point it should be remembered that Eq. (1) is basically obtained by dimensional analysis from the governing parameters of the problem. For the type of problem which we consider here, these are the parameters K, a, t, and another parameter (called Q in Ref. 2) which comes from the boundary condition. As discussed in Ref. 2 the parameter Q is equivalent to a boundary condition of the form $S_{HW} = S^* t^\tau$, i.e., to a suitably programmed input into the heat wave (here S^* is a time-independent constant and τ is a time exponent). S^* and τ may be obtained by dimensional analysis for a given Q. For a closed cavity the boundary condition is $S_{HW} = S_s$, i.e., we have $S^* = S_s$ and $\tau = 0$ (S_s represents the parameter Q). For open geometry (i.e., $n^{-1} > 0$) Q is given by T_∞ (in the limit $t \to \infty$). Dimensional analysis gives in this case $\tau = -\frac{1}{2}$ for our choice of δ, μ, j, and μ'.

Thus rewriting Eq. (1) in terms of $S_r = \sigma T^4$, noting that $S_v \equiv S_{HW} = S_s$ for a closed cavity, and eliminating S_{HW} with the help of Eq. (4), one obtains the desired relation as an implicit equation for S_r,

$$S_r = c t^\alpha (S_s - n^{-1} S_r)^\beta \, . \tag{6}$$

It can be easily verified that Eq. (6) connects the two limiting cases mentioned above.

The constant c and the exponents α and β are determined by comparison with Eq. (1) or one of the specialized equations (2a) or (2b). It should be mentioned that the constant c depends on $\tilde{S}_v$, whose value changes slightly from one limiting case to the other ($\tilde{S}_v = 1.33$ for the boundary condition of a given heat flux and $\tilde{S}_v = 1.01$ for boundary condition of a given temperature, see Ref. 2). Because our cavities are nearly closed, we ignore here this slight change and keep c fixed in the evaluation of Eq. (6). The constant c was determined either by comparison to Eq. (2a) (gold opacity) or Eq. (2b) (maximum opacity). The implicit equation (6) was then solved numerically. Figure 3 shows the flux enhancement S_r/S_s at time $t = 300$ ps as a function of the fractional hole area n^{-1} with the opacity and source flux as parameters. Besides the cases of gold opacity and maximum opacity the curve corresponding to a perfectly reemitting wall with $r = 1$ (labeled perfect reemitter) is also shown. It is given by $S_r/S_s = 1/n^{-1}$ [from Eq. (4) with $S_{HW} = 0$]. This curve is also the limiting curve for $t \to \infty$ for any opacity (provided it leads to a temperature which rises with time).

A cavity without holes corresponds to $n^{-1} = 0$; the intersection of the curves with the vertical axis at $n^{-1} = 0$ yields the N values for such a cavity. It is seen that N is the higher, the higher the opacity and the source flux are. If holes are admitted in the cavity ($n^{-1} > 0$) the flux enhancement S_r/S_s decreases the more rapidly the higher its value for a closed cavity is. This means simply that in a cavity with highly reemitting walls the losses through even small holes have a noticeable influence.

The cavities used in the experiments fall into three categories, each one represented by an arrow. It is seen that for the experimentally realized source fluxes ($< 5\times 10^{20}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$) and gold opacity the flux enhancement is not yet expected to become large and its degradation through the holes is a minor effect, even for the cavities with the largest holes ($n^{-1} = 0.25$).

We note that the intersection of the curves with the vertical axis at $n^{-1} = 1$ yields the reemission coefficient r of the wall for open geometry. This can be seen from the definition of r, noting that $S_i = 0$ for open geometry.

III. CAVITY WITH A CONVERSION LAYER

The experimental observations suggest that a clear spatial separation between the region of generation and deposition of the primary x rays does not exist in 1.3-μm irradiations. In the analysis one should therefore be prepared for a situation where the primary x rays are produced all over the inner surface of the cavity including the observed wall element [scenario (b)]. Internal reflections of laser light in the cavity or heat transport by electrons through a background plasma could lead to

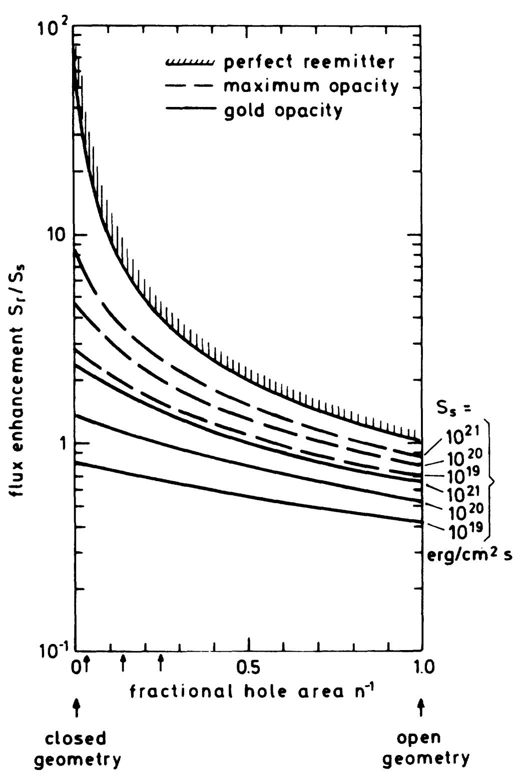

FIG. 3. Flux enhancement S_r/S_s vs the fractional hole area n^{-1} of the cavity. Parameters are the source flux S_s and the opacity of the wall material. The arrows under the horizontal axis correspond to the cavities used in the present experiment.

such a situation.

Whenever the energy flux arriving at the wall is deposited in a layer which is thin for its own thermal radiation, the formation of a conversion layer is expected. Typical for this case is a laser-irradiated wall (Fig. 4). The laser light is absorbed in the low-density, optically thin conversion layer where it is partially converted into x rays. The x rays produced in the conversion layer represent the source radiation for the ablative heat wave which forms in the wall. The dense, optically thick heat wave mediates multiple reemission of the x rays circulating in the cavity. If the observed wall element carries a conversion layer, the registered radiation comes not only from the reemission zone but also from the conversion layer. The main purpose of the following discussion is to clarify the relative importance of the two contributions. We make no attempt to calculate the radiation from the conversion layer but consider it as given. We note, however, that for the limiting case of a conversion layer governed by electron heat conduction, its characteristics have been obtained by dimensional analysis.[10]

Let us assign a conversion efficiency $\alpha = S_c/S_L$ to the conversion layer where S_c is the total radiation flux out of the optically thin conversion layer (counting both directions) and S_L is the absorbed laser flux. The source radiation for the ablative heat wave is then composed of two parts, the fraction $S_c/2$ emitted by the conversion layer towards the wall, and the contribution from the conversion layer on the opposite wall $S_c(1-n^{-1})/2$ which reaches the heat wave through the optically thin conversion layer. Thus S_s is given by

$$S_s = S_c/2 + (1-n^{-1})S_c/2$$
$$= (\alpha S_L/2)[1+(1-n^{-1})] \ . \quad (7)$$

We denote by $S_{\rm rad}$ the total flux radiated towards an observer looking into the cavity. The reemitted flux S_r from the reemission zone is obtained by subtracting the contribution of the conversion layer from the total flux

$$S_r = S_{\rm rad} - \alpha S_L/2 \ . \quad (8)$$

Equations (7) and (8) allow us to determine S_s and S_r, the quantities characterizing the reemission zone, from S_L and $S_{\rm rad}$, the experimentally measured quantities (provided an assumption about α is made). On the basis of S_s and S_r a comparison with the theoretical predictions for radiation confinement by the ablative heat wave can then be made. The predicted value of S_r is obtained by solving Eq. (6) for a given value of S_s as described in Sec. II B.

For the following discussion we write $S_{\rm rad}$ in terms of N by eliminating S_r in between Eqs. (8) and (5). One obtains

$$S_{\rm rad} = \left[\left[\frac{1+(1-n^{-1})}{N^{-1}+n^{-1}} \right] + 1 \right] (\alpha S_L/2) \ . \quad (9)$$

Let us consider for illustration the two limiting cases with $n^{-1}=1$ (open geometry) and $n^{-1}=0$ (closed geometry).

For open geometry one finds

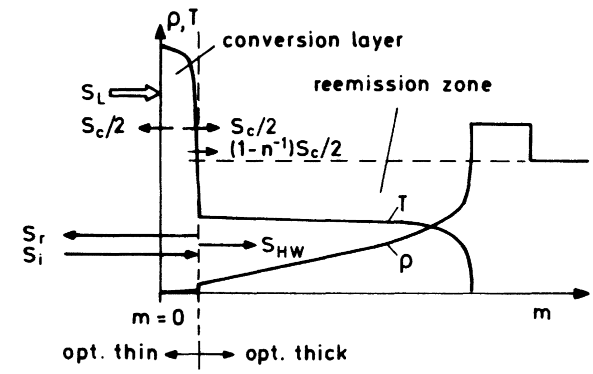

FIG. 4. Ablative heat wave driven by an optically thin, laser-heated conversion layer. S_L is the absorbed laser flux, $S_c/2$ the x-ray flux leaving the conversion layer in one direction, $(1-n^{-1})S_c/2$ the x-ray flux received from the conversion layer on the opposite wall, S_r the reemitted flux, S_i the incident flux received from the ablative heat wave existing on the opposite wall, and S_{HW} the net heat flux into the wave.

$$S_{\rm rad} = \left[\frac{N}{N+1} + 1 \right] \frac{\alpha S_L}{2} = \frac{r+1}{2} \alpha S_L \ . \quad (10)$$

Because $r<1$ the larger part of the radiation seen by an observer comes directly from the conversion layer. The radiation emitted by the conversion layer towards the wall is not entirely used for wall heating but is partially reemitted as blackbody (or actually blackbodylike) radiation by the heat wave.

Equation (10) may be used to calculate the conversion efficiency $S_{\rm rad}/S_L$ of a wall (not to be confused with the efficiency α of the conversion layer) if α is known. For a time of 300 ps, values for r can be read from Fig. 3. For maximum opacity and for $\alpha=1$ one obtains the upper limit of the conversion efficiency of a wall for any source from Eq. (10).

For closed geometry one finds

$$S_{\rm rad} = \left[N + \frac{1}{2} \right] \alpha S_L = \left[\frac{r}{1-r} + \frac{1}{2} \right] \alpha S_L \ . \quad (11)$$

For $N \gg 1$ (or $r \approx 1$) the situation is now quite different from the open geometry. The flux radiated by the wall is dominated by the blackbody radiation from the radiation heat wave and the contribution of the conversion layer to the radiated flux is small. In this limit the difference between an x-ray-heated cavity and a cavity with a conversion layer disappears. However, if N is only of order unity as in the experiments which we want to analyze, the radiation from the conversion layer should be taken into account.

IV. COMPARISON OF EXPERIMENT AND THEORY

In this section we compare the experimental results of papers I and II with our theoretical predictions. The emphasis is on the radiation confinement in the cavity, i.e., on the spectrally integrated flux. The spectrum of the radiation and its deviations from a Planck spectrum have been discussed elsewhere.[8]

As described in paper I, the time-integrated data were corrected by subtracting the contribution from sources located in the volume of the cavity. The primary plasma expanding into the cavity (see paper II) and the wall plasma filling the cavity during the cooling phase are potential sources in this respect. The volume radiation was separately measured along a line of sight passing through two holes in the cavity [spectra before and after correction are shown in Fig. 7(b) in Sec. III D 3 of paper I]. The correction is largest in small cavities and may result in a reduction of the measured spectrally integrated energy density by more than a factor of 2. It is clear that the subtraction is necessary for scenario (a) where it is assumed that the radiation is emitted by the x-ray-heated wall. It is, however, also performed for the 1.3-μm experiments which are analyzed according to scenario (b). In this case it could be argued that the radiation emitted during the laser heating from the volume of the cavity (a detailed discussion has been given in paper II) should be considered as radiation from the conversion layer which we have allowed for in the theoretical model. If we subtract it we take a conservative attitude, attempting to avoid an overestimation of the radiation confinement in the cavity.

The experiments presented in paper I have shown that for 0.44-μm irradiations a primary plasma is generated at the back wall of the cavity as assumed in scenario (a). Hence we compare the 0.44-μm results with the theoretical predictions for scenario (a) (see Fig. 5). For simplicity the theoretical curves are given only for the most frequently used cavity with $n^{-1}=0.14$. For each experiment two values of the source flux are given, connected by a horizontal line. One of them (circles) corresponds to the (unrealistic) assumption that the absorbed laser flux is

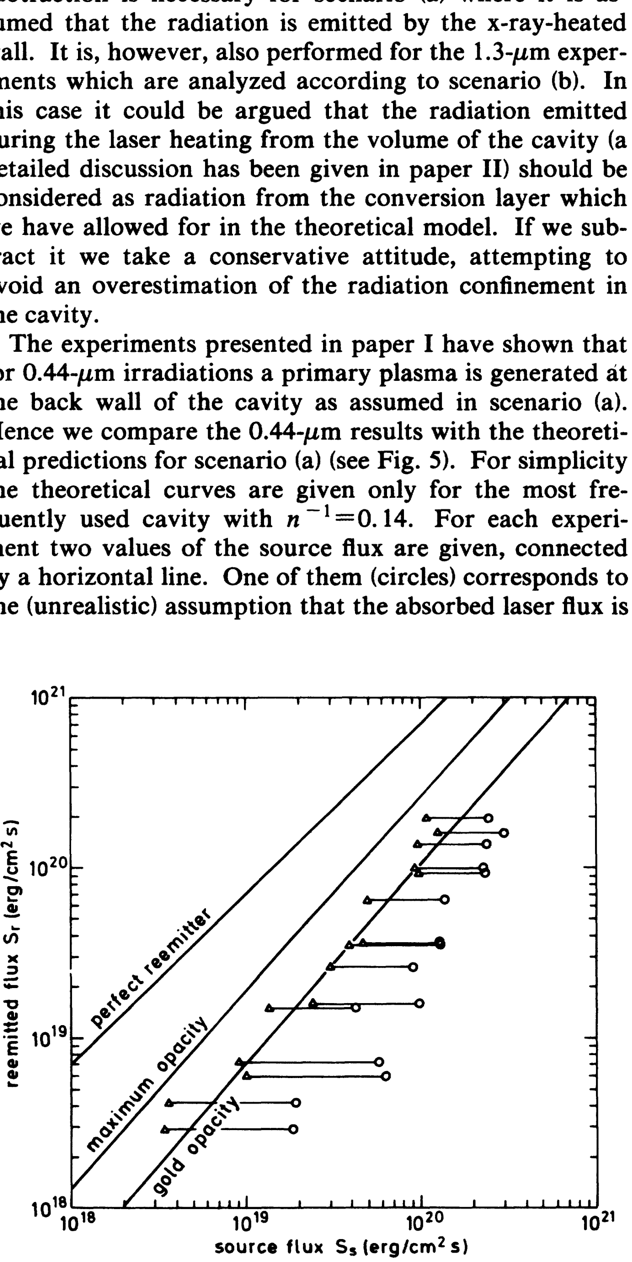

FIG. 5. Reemitted flux S_r vs source flux S_s (0.44-μ-laser) for scenario (a). The experimental points are obtained either (Δ) using the measured x-ray conversion efficiency at the back wall of the cavity or ($\bigcirc$) assuming complete conversion of laser light into x rays. The theoretical curves are for the standard cavity with $n^{-1}=0.14$.

completely converted into x rays. The other one (triangles) is based on the measured conversion efficiency at the back wall of the cavity as described in Sec. III D 4 of paper I.

As expected, the values of S_r predicted for a perfectly reemitting wall where S_r is determined by the loss of radiation through the hole, are by far not reached in the experiments. Also the values predicted for a wall with maximum opacity are still significantly above the experimental points. However satisfactory agreement of the experimental points (triangles) is obtained for a wall with our calculated gold opacity, i.e., for the most realistic available prediction. But it is essential that the experimentally determined conversion efficiency (typically 0.3) is taken into account; with the assumption of complete conversion (circles) the measured flux would remain below the expectations.

From the experimental points the quality factor N for radiation confinement can be estimated. At the upper end of the range of measurements the triangles yield a ratio $S_r/S_s \cong 1.5$. With $n^{-1}=0.14$ one finds from Eq. (5) $N \cong 2$, i.e., in a completely closed cavity x rays would be about two times reemitted. This evaluation is based on a radiation time of the cavity of 300 ps as assumed in paper I. The streak camera measurements presented in paper II yield typically a radiation time of 550 ps which would yield $N \cong 1$. This value is considered as lower bound because with our correction procedure we subtracted at least partly the radiation emitted during the cooling of the cavity. Thus our analysis suggests that the quality factor is in the range $N \cong 1-2$, corresponding to values of the reemission coefficient r in the range $r \cong \frac{1}{2}-\frac{2}{3}$.

Let us now consider the results obtained in 1.3-μm irradiations. The experiments described in papers I and II have shown that in this case plasma filling of the cavity complicates the situation considerably and a clear spatial separation between the generation and deposition of the primary x rays apparently does not exist. We attempt therefore a comparison of the results with scenario (b). Because the efficiency α of the conversion layer could not be measured in the experiments, it is treated as a free parameter. S_r and S_s, the quantities characterizing the ablative heat wave (reemission zone), were determined with the help of Eqs. (7) and (8) from S_L and $S_{\rm rad}$, the measured quantities. Thus the results, shown in Fig. 6, appear as a curve for each experiment along which α varies. As can be verified from Eqs. (7) and (8), the measured quantities $S_{\rm rad}$ and S_L can be read from the curves by noting that S_r is equal to $S_{\rm rad}$ in the limit $\alpha=0$ and S_L is equal to S_s in the limit $\alpha=1$ [for $n^{-1}=0$, see Eq. (7)]. The theoretical curves shown in Fig. 6 are identical with those shown earlier in Fig. 5.

Figure 6 may be commented upon as follows: One expects that the cavity wall confines the energy received in the form of x rays from the conversion layer in the same manner as it confines the primary x rays in the 0.44-μm irradiations. Thus the experimental results should be again consistent with the theoretical prediction for the gold opacity. As can be seen from the intersection of the experimental curves with the theoretical curve for gold opacity, this would be the case if the efficiency α of the

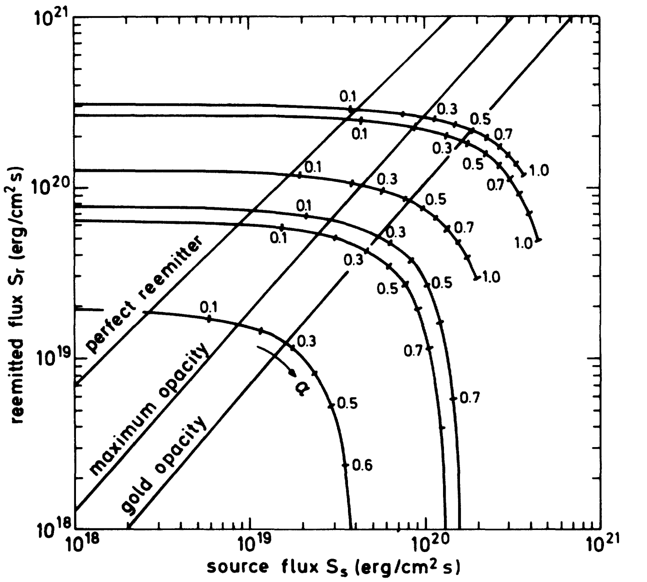

FIG. 6. Reemitted flux S_r vs source flux S_s (1.3-μm laser) for scenario (b). Each curve corresponds to a single experiment with α, the efficiency of the conversion layer, being treated as a free parameter. The theoretical curves correspond to the preceding figure.

conversion layer were in the range $0.3 < \alpha < 0.5$.

It is possible to obtain an independent estimate which shows that such values for α are not unreasonable. The estimate is derived from measurements of the x-ray conversion efficiency made with 1.3-μm laser light on open, planar gold targets.[10] The conversion layer which forms on a planar target heated by near-infrared 1.3-μm laser light is governed by electron heat transport. Provided the conversion layer in a cavity is dominated by the same mechanism and provided the characteristics of electron heat transport do not change strongly upon transition to closed geometry, the values of α derived from experiments in open geometry should come close to the values found above. α can be obtained from Eq. (11) by using measured values for $S_{\rm rad}/S_L$ and calculated values for r. The measurements give $S_{\rm rad}/S_L \simeq 0.25$ at $S_L = 10^{13}\,\mathrm{W\,cm^{-2}}$ (a typical value for the average absorbed laser flux in our experiments) for a laser-pulse duration of 300 ps. For r one reads from Fig. 3 $r \simeq 0.55$ at this laser flux. Equation (11) gives then $\alpha \simeq 0.32$. It is interesting to see that this value falls into the range of α which has been obtained through the analysis of the cavity experiments. Most likely α decreases with the laser flux and causes to a large part the reduced wall efficiencies measured in planar target experiments[10] (see also the references in paper I), as well as the degradation in the efficiency of cavity heating observed in 0.53-μm irradiations[11] at higher laser flux ($> 10^{14}\,\mathrm{W\,cm^{-2}}$) than used here.

In summary, we have analyzed a series of laser cavity heating experiments from the point of view of radiation confinement in the cavity. The analysis shows that a quality factor of $N \cong 1-2$, respectively, a reemission coefficient of the wall of $r \cong \frac{1}{2}-\frac{2}{3}$ has been obtained in the experiments. This result is in agreement with theoretical predictions on the basis of the self-similar ablative heat wave. The main limitation with respect to the accuracy of our analysis is connected with the difficulty to obtain precise information about laser light conversion in the inaccessible geometry of a closed cavity and with the complexity of the conversion process. For short-wavelength irradiations, where the steps leading to cavity heating seem rather well defined, we are optimistic that further progress towards a more quantitative and detailed understanding of radiation confinement may be obtained. In long-wavelength irradiations the complexity of the phenomena may be prohibitive.

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