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Cavities for the generation of "clean" Planck radiation by pulsed laser beams

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ABSTRACT

In the generation of intense Planck radiation in a laser-heated cavity one encounters the problem that the cavity fills rapidly with hot, laser-produced plasma from the cavity wall. In this report we discuss the possibility to convert the laser light into thermal radiation outside the main cavity and to introduce the energy in the form of x-rays. Calculations are presented for the transfer efficiency through a hole in a laser-heated converter cavity. Parameters are the absorbed laser flux, the fractional hole area and the opacity of the wall material.

I. Introduction

Recent attempts to generate intense Planck radiation in the x-ray spectral range in a laser-heated cavity[1–5] have shown that the introduction of the energy in the form of laser light may lead to rapid filling of the cavity with very hot (~ 1 keV) plasma from the laser - irradiated wall. The presence of this plasma complicates the spectra of the emitted radiation[1–4], may lead to fast electron generation[6,7] by nonlinear laser plasma coupling, and is therefore in general undesirable in applications such as inertial confinement fusion where one intends to expose an object to thermal radiation under the clean conditions of an vacuum environment. In this report we discuss some ideas how a "clean" radiation field could be established by converting the laser light into x-rays outside the main cavity and introducing the energy in the form of x-rays. In this case a hot laser-produced plasma does not form in the cavity and filling with evaporated wall material occurs at a much slower rate determined by the temperature (~ 0.1 keV) of the x-ray heated wall material.

II. X-ray transport by reemission

Fig. 1(a)-(h) illustrates some possibilities how the energy supplied by a laser or particle beam can be transported in the form of x-rays into a cavity.

In Fig. 1(a) a main cavity has been joined (whence we suggest the name JOINT cavities for the class of cavities discussed in this report) together with two smaller converter cavities. In the converter cavities the laser irradiates the wall and is - in general after several reflections - partially converted into x-rays. Depending on conditions the energy is then several times reemitted in the form of thermal x-rays in the cavity[8]. The larger is the effective number of reemissions, the larger is the fraction of the converted laser energy which is transferred through the connecting hole to the main cavity. The converter cavities, if driven hard by the laser will tend to fill up rapidly with hot laser-produced plasma from the wall. However, because the x-rays propagate with the speed of light, it is conceivable that the laser-produced plasma (speed $10^7 - 10^8 cm/s$) which first expands into the converter cavity and only later into the main cavity arrives too late to affect the formation of a "clean" radiation field in the main cavity. Furthermore the x-rays transferred into the main cavity have in general been several time reemitted. Thus they have a relatively soft spectrum corresponding to the temperature of the x-ray heated material in the wall of the converter cavity. The main cavity and any object placed in it is therefore not, or at least only to a minor extent, exposed to the harder primary x-rays which are generated in the hot laser-produced plasma. Thus the spatial separation of the conversion process has also a cleaning effect on the spectral distribution of the radiation.

In the design shown in Fig. 1(a) three spherical cavities have been joined. The main motivation for such a design is the fact that in a spherical cavity a Lambert radiator located on the cavity wall irradiates the interior of the cavity uniformly, facilitating theoretical modelling (the Ulbricht spherical photometer makes use of this property of a sphere). In practice the converter cavities may have a different shape which has been optimized with respect to constraints like the given configuration of laser beams etc. For illustration Fig. 1(b) shows a case where the x-rays fall through an annular ring into the main cavity. Laser light can reach the main cavity only after two reflections when most of it might have been absorbed. Also the primary x-rays produced at the first encounter of the laser beams with the wall are prevented from entering the main cavity. Note that in these as well as in the following designs it is assumed that the laser beams arrive in two clusters from opposite sides as they do in most multi-beam installations. Similar considerations may be made for other configurations of the laser beams.

It is also useful to look at the cavities of this general type in a slightly different manner. As shown in Fig. 1(c) one may think of a long cylinder which is heated at the ends by laser beams. The length of the cylinder and the introduction of a stop for the laser light quarantees that the central section (where the object to be irradiated would be placed) is reached only by thermal x-rays which are multiply reemitted from the wall as they diffuse down the tube. Reemission from the wall has a smoothing effect on the angular distribution of the radiation and eliminates any hard radiation generated during laser-plasma interaction. The primary laser-produced plasma expands away from the central section of the tube and can reach it only after being reflected from the wall at the end of the cylinder, increasing the delay to plasma filling. The length of the tube cannot, however, be made arbitrarily long because with each reemission a fraction of the energy is transformed into internal and kinetic energy of the heated wall material and lost. If the length of the tube is shortened and the contours rounded in order to avoid the formation of corners one arrives at a design as shown in Fig. 1(d). If the laser energy is introduced in the central section as shown in Fig. 1(e) the radiation diffuses first towards the ends and then returns to the central section of the tube. In this case one is lead to a design as shown in Fig. 1(f). Fig. 1(g) is meant to illustrate the point that the radiation in a tube can diffuse around a corner whereas any energy transported on straight trajectories could not reach the central section of the tube. Whereas Figs. 1(a)-(g) have the appropriate symmetry for the two-sided irradiation of an object, Fig. 1(h) reminds to the possibility of using similar designs for the one-sided irradiation of an object.

It is clear that the above considerations are only of a qualitative nature. Whether design (b),(d), or (f) or some other design is more suitable can only be determined by more detailed calculations after the object to be irradiated has been specified. The task then is to find the optimal cavity shape for given irradiation conditions (e.g. uniform irradiation of a spherical fusion capsule) by calculating the transport of energy from the introduction in the form of laser light up to its arrival at the irradiated object in the form of thermal x-rays. This difficult problem is beyond the scope of this report.

III. An approximate calculation of the transfer efficiency

It is possible to carry out an approximate calculation of the efficiency of energy transfer in the form of Planck radiation through the hole of a spherical converter cavity. Although a special case, it could be investigated experimentally; Fig. 1(a) shows a cavity design where it applies. For other designs it may still give a feeling of the expected transfer efficiencies.

As in Ref.[5] (see ibid Fig. 1(b)) we consider a spherical cavity which is uniformly irradiated by laser light. Laser irradiation of the wall generates a conversion layer which is optically thin for the emitted primary x-rays. With S_L the absorbed laser flux at the wall and S_c the total flux of x-rays emitted by the conversion layer (counting both directions), its efficiency is defined as $\alpha = S_c/S_L$. Radiation heat conduction into the depth of the wall leads to the formation of a reemission zone which supports the circulating flux of Planck radiation in the cavity.

The input of primary x-rays from the conversion layer into the reemission zone, called the source flux S_s, is given by

$$S_s = \frac{S_c}{2} + (1 - n^{-1})\frac{S_c}{2} = (1 + (1 - n^{-1}))\frac{\alpha S_L}{2} \quad . \qquad (1)$$

The first term represents the primary x-rays which the conversion layer emits directly into the adjacent wall. The second term is the contribution from the other wall elements of the cavity in which the holes occupy a fractional area $n^{-1}(n^{-1} = A_h/(A_h + A_e)$ where A_e and A_h are the material (emitting) and hole areas, respectively.) It is assumed here that the primary x-rays irradiate the interior of the cavity (wall as well as holes) uniformly. This assumption would be strictly valid for a Lambert radiator irradiating a spherical cavity. The reemission zone receives a flux S_i of incident circulating x-rays and reemits a flux S_r of x-rays. It has been shown in Ref.[5] that, with the help of dimensional analysis, the ratio S_r/S_s can be approximately calculated as a function of time. Noting that in the presence of holes we have (similarly as for the primary x-rays)

$$S_i = (1 - n^{-1})S_r \quad , \qquad (2)$$

one obtains for the transfer efficiency ς through the holes with the help of Eqs. (1) and (2)

$$\varsigma = \frac{primary + circulating\ x{-}rays\ through\ holes}{laser\ power\ into\ cavity}$$

$$= \frac{A_h((1 - n^{-1})\frac{\alpha S_L}{2} + S_i)}{A_e S_L} = n^{-1}\frac{\alpha}{2}\left(1 + \left\{1 + (1 - n^{-1})\right\}\frac{S_r}{S_s}\right) \quad . \qquad (3)$$

In the manner described in Ref.[5] we have calculated the flux enhancement S_r/S_s for times of 300 ps, 1 ns and 3 ns and for source fluxes between 10^{12} and $10^{15} W cm^{-2}$. Fig. 2 shows results obtained on the basis of the Rosseland opacity calculated for gold in[9]. Fig 3 has been calculated for a material with maximum opacity according to the theorem by Bernstein and Dyson[10]. It is seen that the flux enhancement S_r/S_s is largest for a closed cavity ($n^{-1} = 0$) and increases with the source flux and the irradiation time τ. For maximum opacity the values are considerably higher than for gold opacity. For $n^{-1} = 1$ the calculations give the result for a planar wall. The laser flux S_L related to the source flux S_s can be obtained from Eq. (1) when α and n^{-1} are specified.

Figs. (3) and (4) show the transfer efficiency ς for the same set of calculations. Because ς is proportional to the efficiency α of the conversion layer all curves are given for α=1. ς is zero for n^{-1}=0 i.e., for a closed cavity without a hole. For a given transfer efficiency the hole can be made the smaller the higher the source flux is and the longer the irradiation time. Maximum opacity gives again considerably more favourable results.

IV. Conclusions

Our calculations have shown that it might be possible to transfer energy efficiently in the form of thermal x-rays from a laser-heated cavity. A high transfer efficiency calls for a large laser flux, long irradiation time and maximum material opacity. The largest uncertainty lies in the primary conversion step of laser light into x-rays which we have not considered here. Provided a high conversion efficiency can be achieved by short wavelength lasers it may be possible to generate a "clean" radiation field in cavities without the complications arising from the presence of the laser-produced plasma.

V. Acknowledgement

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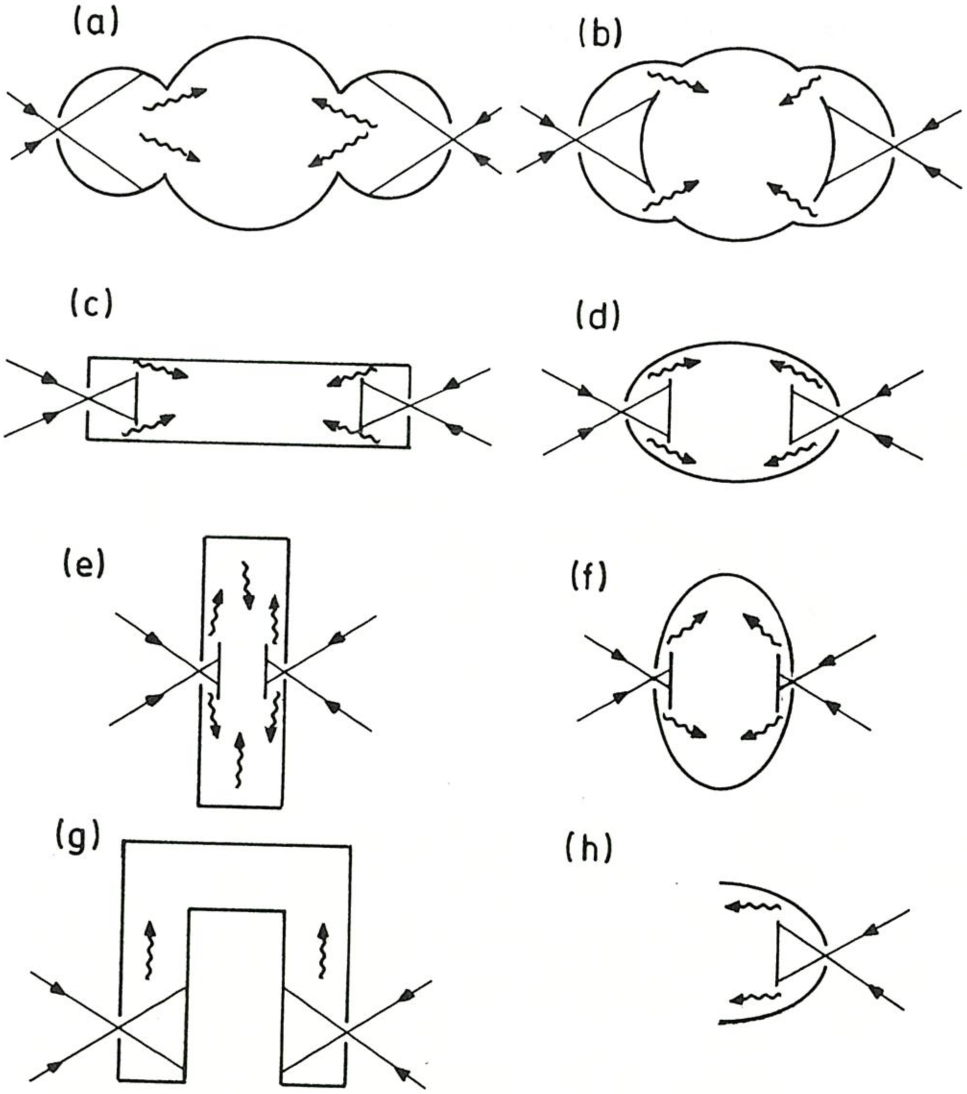

Fig. 1: (a) - (h): Schematic illustration of some possibilities for the transfer of energy by multiple reemission of laser-generated thermal x-rays.

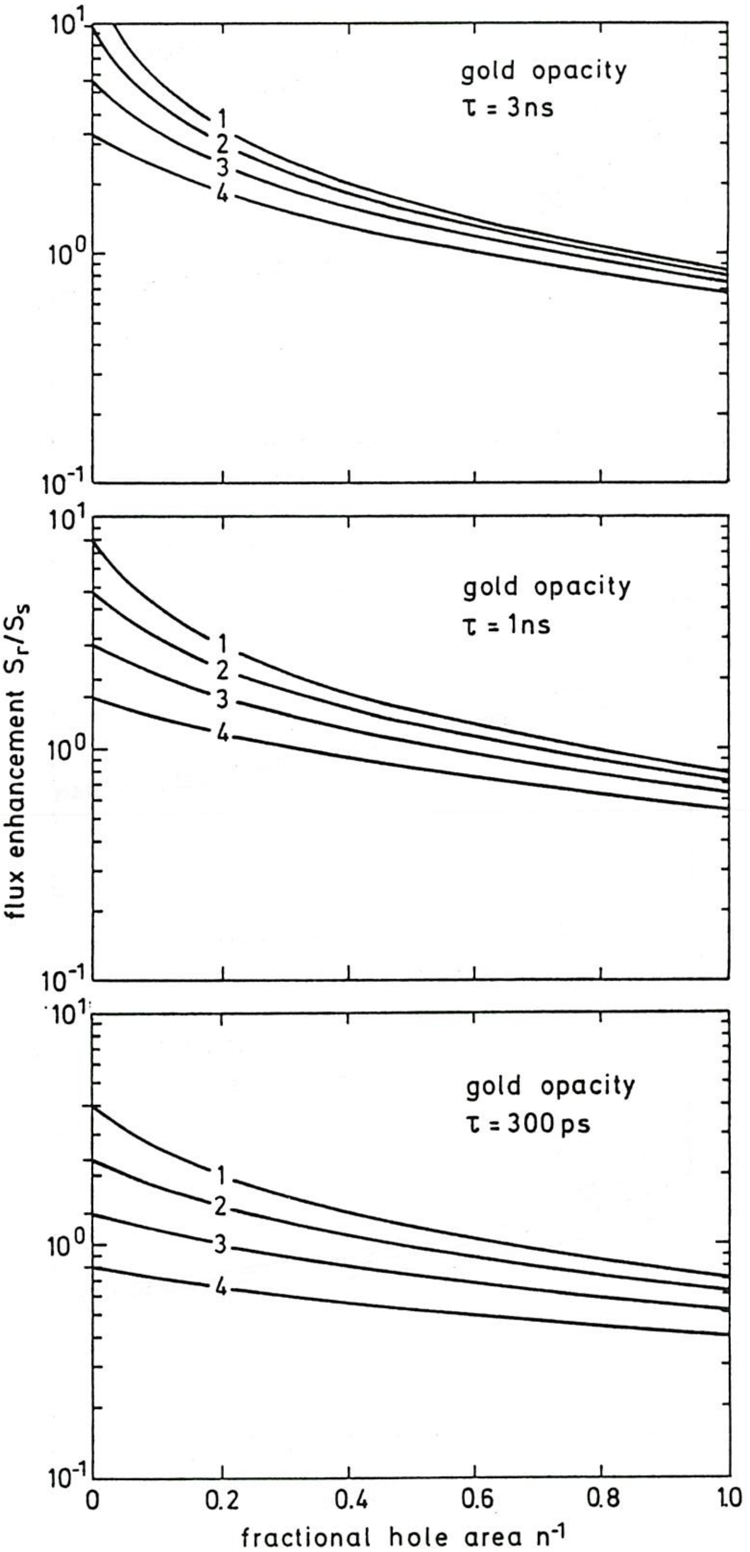

Fig. 2: Flux enhancement S_r/S_s versus the fractional hole area n^{-1} for a gold wall after an irradiation time of 3 ns, 1 ns, and 300 ps. The curves 1 - 4 were calculated for values of the source flux S_s of $1 : 10^{15} W cm^{-2}$, $2 : 10^{14} W cm^{-2}$, $3 : 10^{13} W cm^{-2}$, $4 : 10^{12} W cm^{-2}$.

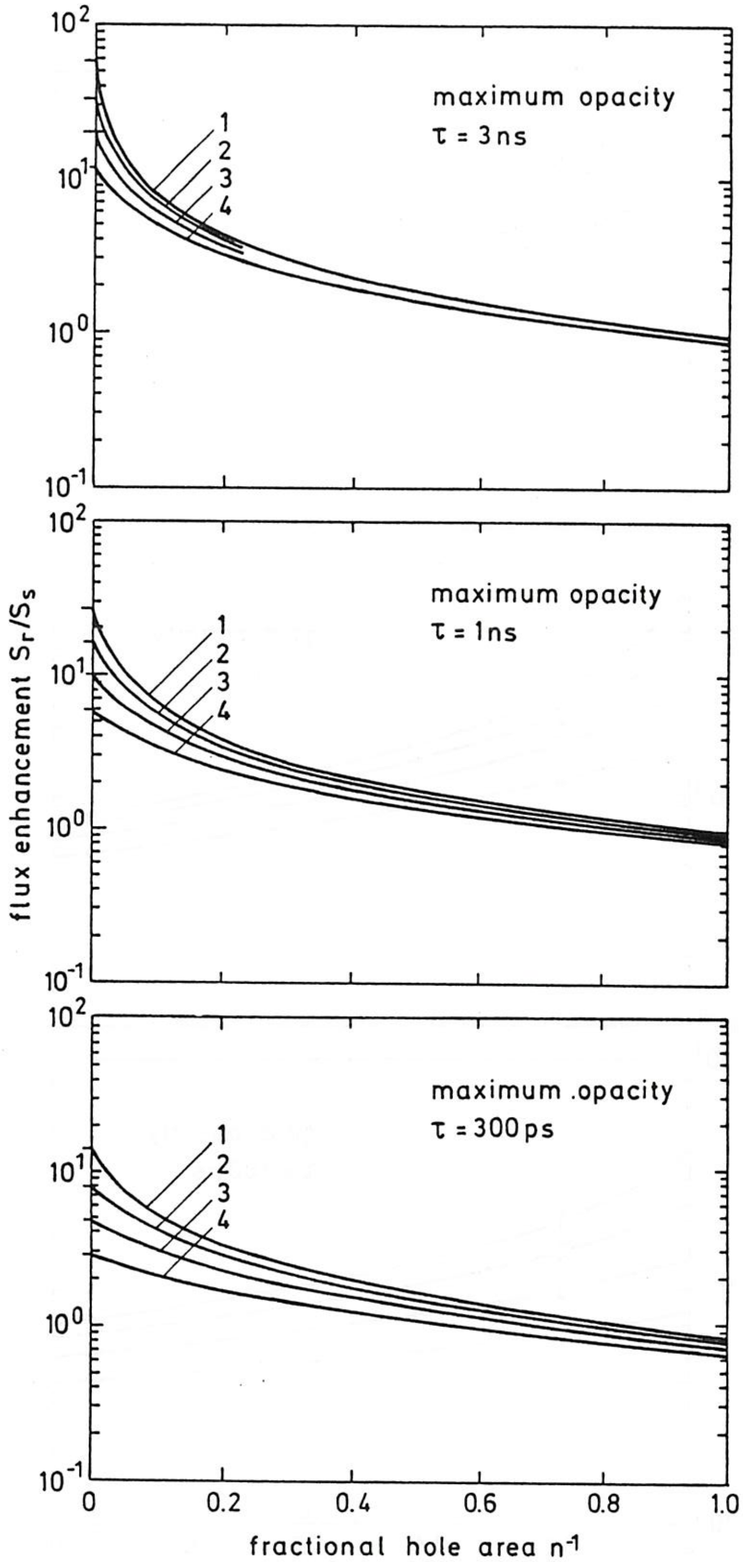

Fig. 3: Same as Fig. 1, but for a wall with maximum opacity .

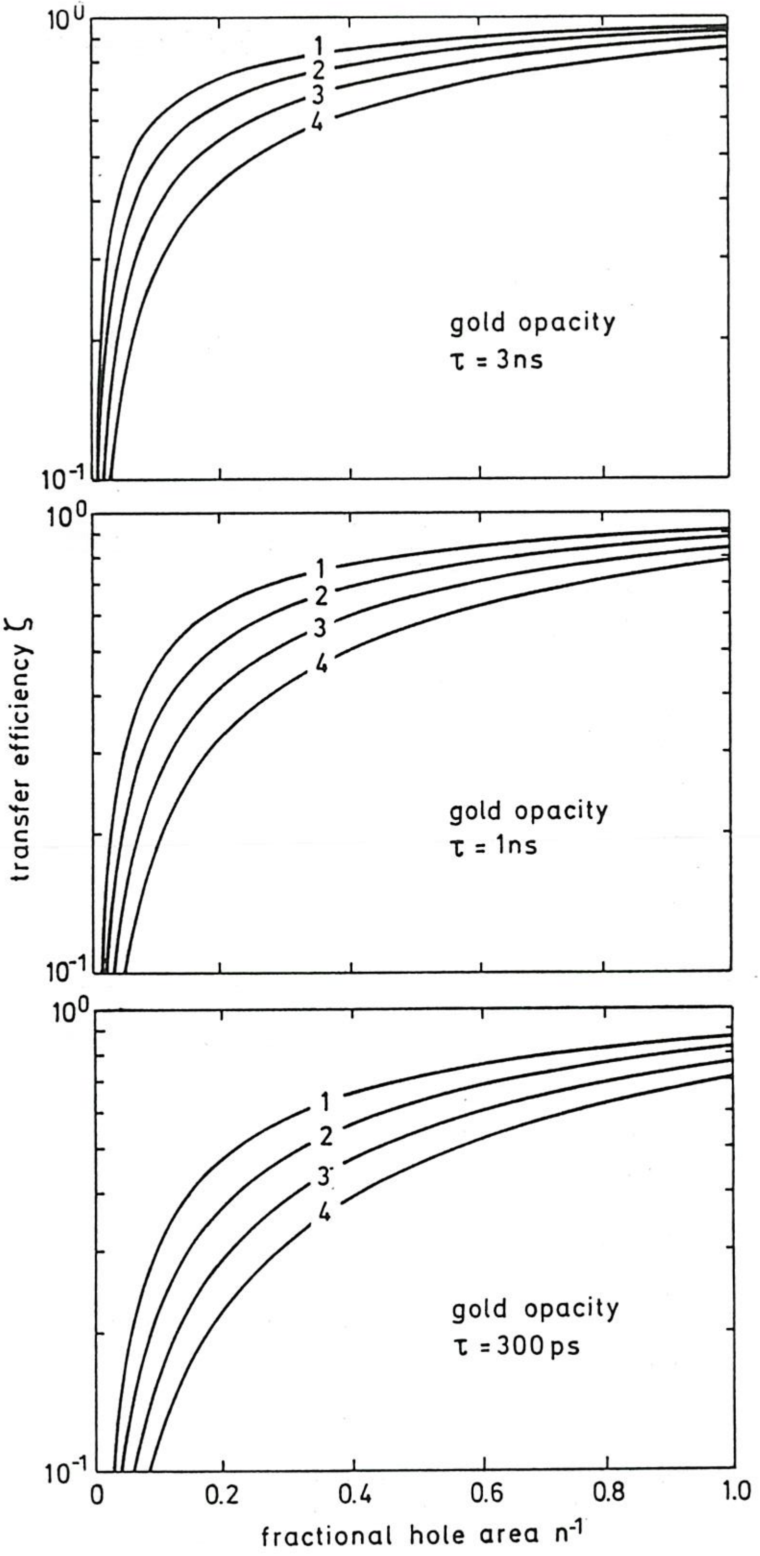

Fig. 4: Transfer efficiency ς *versus the fractional hole area* n^{-1} *for a gold wall. Parameters as in Fig.1 .*

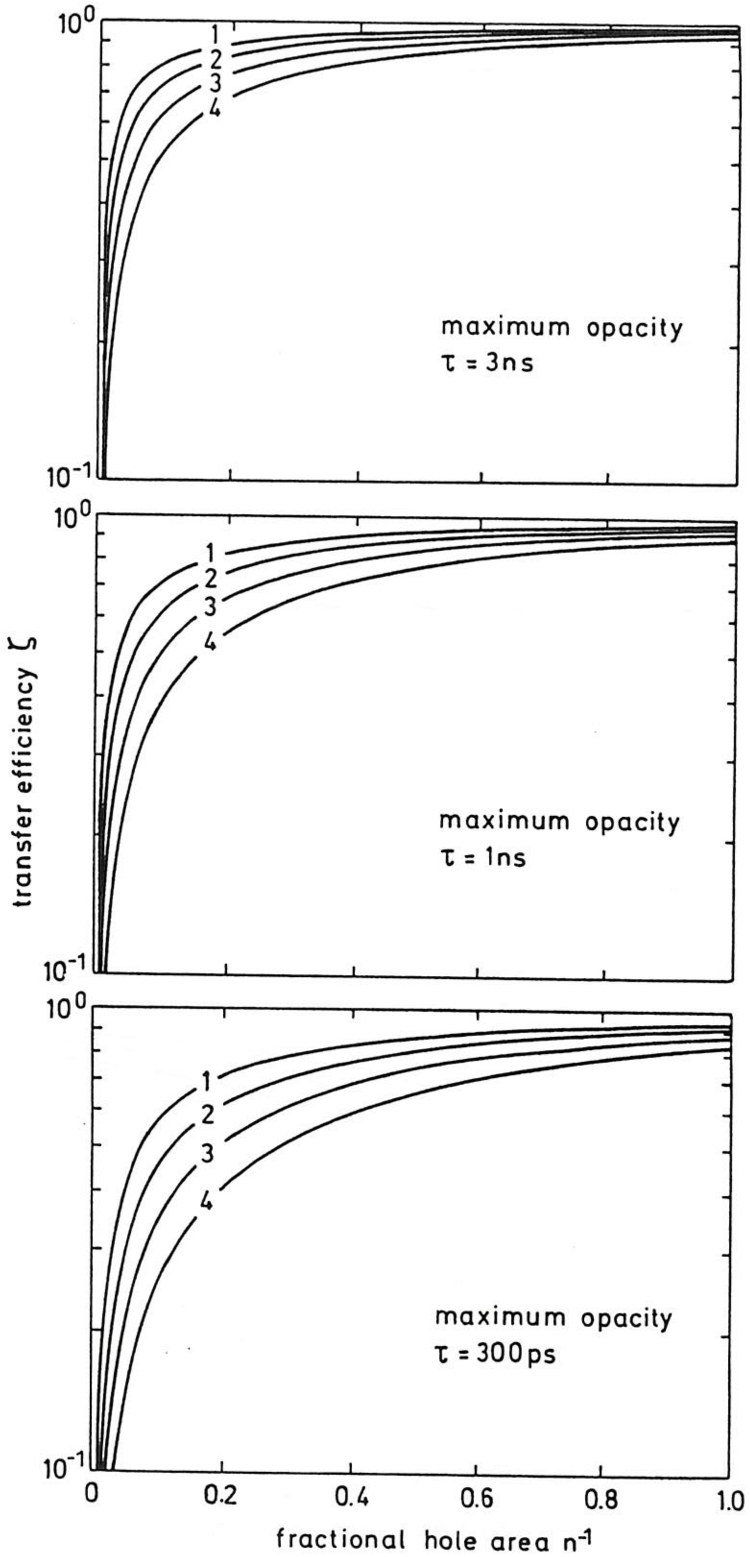

Fig. 5: Same as Fig. 3, but for a wall with maximum opacity .