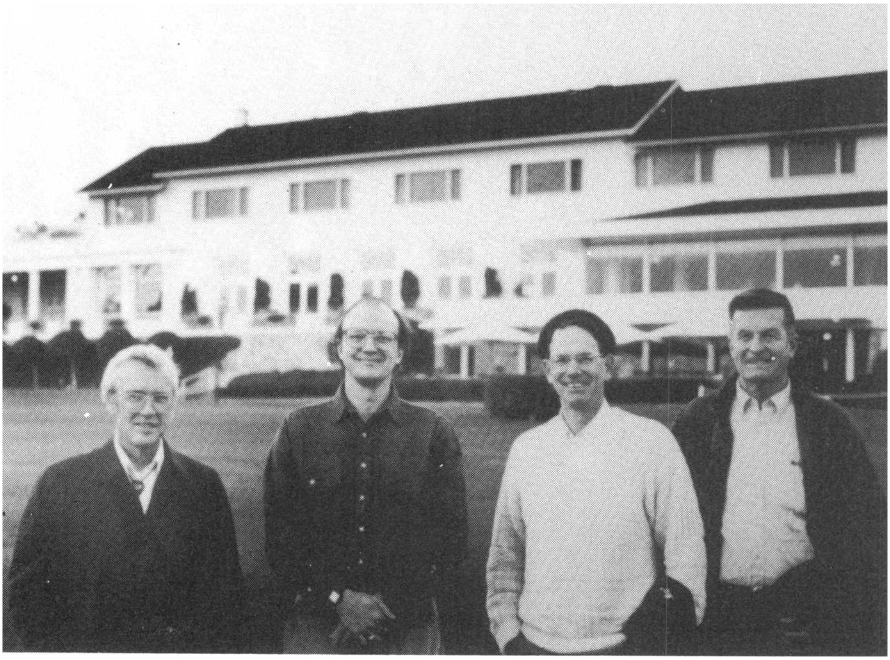
SECTION V

Beam-Target Interactions, Atomic and Muon Physics



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2-D STUDY OF THERMAL X-RAY GENERATION FROM ION-BEAM-HEATED CONVERTERS

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A concept for *converters* of ion beam energy into thermal X-rays, of relevance to inertial confinement fusion (ICF), is studied by means of 2-D radiation hydrodynamics simulations. Cylinders made of low-density, high-atomic-number materials, irradiated by an ion beam parallel to their axis, are considered. A solution is proposed to ensure complete stopping of the beam without degradation of energy conversion. A parametric analysis shows that high conversion efficiency requires specific deposition powers of the order of 10^{16} W/g, in agreement with previous 1-D results. An analytic expression for the conversion efficiency as a function of the converter and beam parameters (and taking 2–D effects into account) is derived which agrees with the simulations and is suitable for application to ICF target design.

1 INTRODUCTION

Heavy ion beams can be used to generate thermal X-rays with properties suitable for utilization in indirect drive Inertial Confinement Fusion (ICF)[1–3]. The simplest concept considered is based on cylindrical *converters*, with radius r_0, irradiated by parallel beams with the same radius r_0. Recently, such configurations have been studied by 1-D simulations[3]. It has been found that for typical ICF parameters the highest values of the conversion efficiency $\eta_x = E_x/E$ (where E_x is radiated energy and E is input energy) are obtained by using low-density, high-Z (atomic number) materials, and that η_x larger than 80% requires specific deposition powers P of the order of 10^{16} W/g.

Converter design, however, requires consideration of the ion-stopping physics (yielding finite range and non-uniform deposition along the ion path); of the finite length of the cylinder; and of the radial profile of the beam. This motivates the present study of cylindrical converters, performed by using the 2-D, 3-temperature Lagrangian code DUED[4], employing an accurate equation of state, along with opacity data in agreement with Ref. 5.

We have also derived (see Section 3) a simple analytical model for the evaluation of η_x as a function of the beam and target parameters, which is in agreement with our 2-D simulations. Besides dependencies on other quantities, we find that η_x depends on the product Rr_0^{δ}, with $\delta \cong 1.5$, which was used to parametrize indirect drive ICF target gain computations[1,2,6] (where R is the ion range in the cold material and r_0 is the initial cylinder radius).

2 TWO-DIMENSIONAL SIMULATIONS

The converters studied in this paper consist of a cylinder, made of gold at low density, ρ_0, with initial radius r_0, and length $L \simeq R/\rho_0$, with a terminal plug of the same material at the ordinary solid density (see Figure 1a).

The evolution of a typical case is shown in Figure 1. Here $r_0 = 0.1$ cm, $\rho_0 = 0.5$ g/cm^3 and $L = 0.5$ cm. The beam consists of Bi ions with energy $\mathscr{E} = 10$ GeV (for which, in Au, $R = 0.28$ g/cm^2); its power $W = 2.63 \times 10^{14}$ W and it has a Gaussian radial profile with half-width $\Delta r_0 = 0.06$ cm. The average deposited specific power is $\langle P \rangle \simeq W/(\pi r_0^2 R) = 3 \times 10^{16}$ W/g. As soon as the converter heats up, the range shortens (Figure 1a), but subsequently the beam edge moves forward (Figures 1b and 1c) due to the expansion of the converter. The terminal plug is necessary to stop completely the outer ring of the beam; indeed, Figure 2 shows that without using the plug, even a cylinder with $L = 1.4\ R/\rho_0$ cannot stop the beam completely. The isotherms clearly show the region of highest temperature around the location of the Bragg peak. Detailed analysis shows that, after a heating stage of duration $t_H \simeq 1$ ns during which radiation emission is negligible, then, for $t_H < t \leqslant 10$ ns, the converter temperature, the radiated power, and the instantaneous conversion efficiency $\tilde{\eta}(t)$ are approximately constant (the latter with the value $\tilde{\eta}(t) = \tilde{\eta}_s$). A fraction $f \simeq (1 + \zeta)^{-1}$, where $\zeta = r_0/(2L)$, of the radiation is emitted from the back surface.

The dependence on ρ_0 and $\langle P \rangle$ of the conversion efficiency η_x and of the efficiency of radiation from the lateral surface only η_x^l, both taken at $t = 10$ ns, are shown in Figure 3. It refers to cases with $r_0 = 0.1$ cm, using Bi ions with $\mathscr{E} = 10$ GeV. Comparison with 1-D simulations with uniform radial deposition show that η_x is only slightly affected by 2-D effects.

3 MODEL FOR THE CONVERSION EFFICIENCY

For modeling situations of interest for ICF, we consider N identical cylinders, each irradiated by an ion beam with constant power W/N (so that the total power is W and the total energy up to time t is $E = Wt$). We assume constant and uniform specific deposition P, estimated as $P = W/(N\pi r_0^2 R)$. Further, we consider situations such that the irradiation time t_p is $t_H < t_p < t_d$, where t_d is the converter disassembling time, and that P is large enough that we have $\tilde{\eta}_s \cong 1$ (it is the possibility of achieving the latter condition with reasonable values of P that makes high-Z materials most attractive for ICF applications[3]). We then approximate the total power radiation output from the N converters by $W_x = 0$ for $t \leqslant t_H$ and $W_x = \tilde{\eta}_s W \cong W$ for $t_H < t < t_d$. Then, for $t_H < t \leqslant t_p < t_d$, we can write $\eta_x(t) = E_x(t)/E(t) = (t - t_H)/t = t_x/(t_x + t_H)$, where $E_x = W_x t_x \cong W t_x$, $E = Wt$, and $t_x(t) = t - t_H$.

In the cases of interest the converter is optically thick, so that $P\pi r_0^2 RN \simeq 4\sigma T_s^4 \pi r_0 NL = W_x = E_x/t_x$, where σ is the Stefan–Boltzmann constant, T_s is the surface temperature of the cylinder, and $L \simeq R/\rho_0$. Following Ref. 3, we take $t_H = e(T_c)/P$, where e is the specific energy, and T_c is temperature on the symmetry axis, and we assume that power law dependencies apply for $e(T) = e_0 T^\mu$, and for the

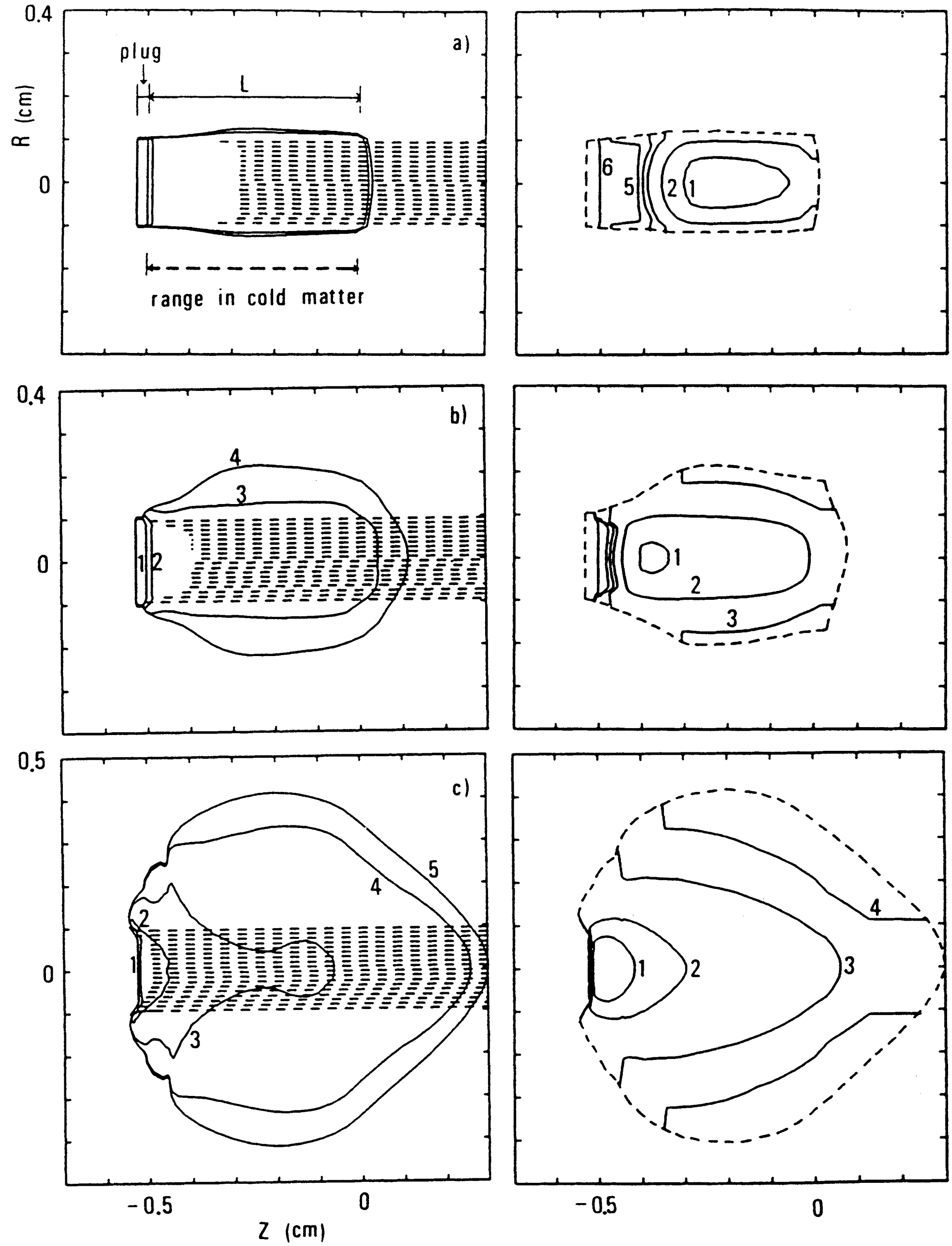

FIGURE 1 Evolution of a converter with the parameters given in the main text. Left column: heavy ion trajectories (dashed) and iso-density contours (1) $\rho = 10$ g/cm^3; (2) $\rho = 1$ g/cm^3; (3) $\rho = 0.1$ g/cm^3; (4) $\rho = 0.01$ g/cm^3; (5) $\rho = 0.0035$ g/cm^3. Right column: iso-(electron) temperature contours (1) $T = 7 \times 10^6$ K; (2) $T = 5 \times 10^6$ K; (3) $T = 3 \times 10^6$ K; (4) $T = 2 \times 10^6$ K; (5) $T = 10^6$ K; (6) $T = 10^5$ K. Three times are shown: (a) $t = 2$ ns; (b) $t = 5$ ns; and (c) $t = 10$ ns.

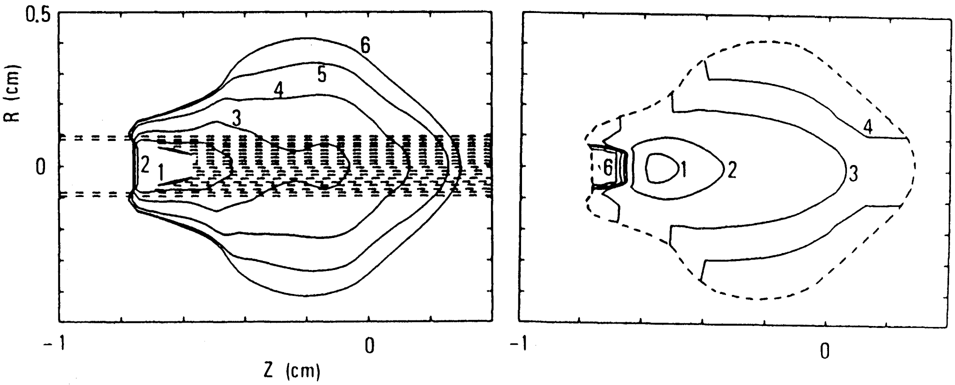

FIGURE 2 Cylinder without high density plug at $t = 10$ ns. Same as in Figure 1, but for the density contours here (1) $\rho = 1$ g/cm^3; (2) $\rho = 0.3$ g/cm^3; (3) $\rho = 0.1$ g/cm^3; (4) $\rho = 0.03$ g/cm^3; (5) $\rho = 0.01$ g/cm^3; and (6) $\rho = 0.0035$ g/cm^3.

Rosseland opacity $l = l_0 T^{\mu} \rho_0^{-\beta}$. We relate T_c to T_s by the large r/l limit of the plane photosphere solution, yielding $T_c = c_1^{\varphi} T_s^{4\varphi}(r_0 \rho_0^{\beta}/l_0)^{\varphi}$, with $c_1 = 3(\alpha + 4)/8$ and $\varphi = 1/(4 + \alpha)$, thus obtaining

$$\frac{t_H}{t_x} = KN^{1-\mu\varphi}(Rr_0^{\delta})^{1+\mu\varphi\beta}\frac{1}{E_x}\left[\frac{E_x}{t_x L^{1+\beta}}\right]^{\mu\varphi}, \tag{1}$$

where $K = \pi c_1^{\mu\varphi} e_0 (4\pi\sigma l_0)^{-\mu\varphi}$. By using Eq. (1) we can express η_x as a function of the beam-target parameters:

$$\eta_x(t) = 1 - KN^{1-\mu\varphi}(Rr_0^{\delta})^{1+\mu\varphi\beta}\frac{(WL^{-1-\beta})^{\mu\varphi}}{E(t)}. \tag{2}$$

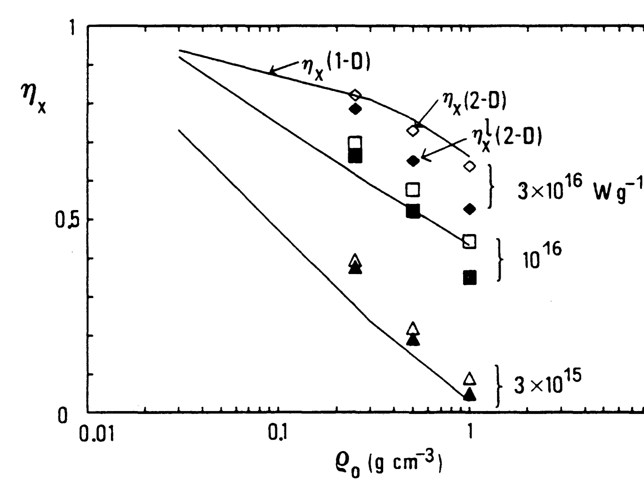

FIGURE 3 Conversion efficiencies η_x (from 1-D and 2-D simulations) and η_x^l(2-D) versus the density ρ_0, for different values of the specific power deposition $\langle P \rangle$.

The exponent $\delta \simeq 1.5$ for many materials (e.g. $\delta = 1.52$ for Au, $\delta = 1.57$ for Al, and $\delta = 1.54$ for CH). It is well known that the parameter $\xi = (Rr_0^{3/2})$ has been used[1,2,6] to parameterize the results of gain computations of indirectly driven ICF targets: the reason is probably the dependence of η_x on ξ, shown by Eq. (2). [Similar results for η_x have been independently derived by Meyer-ter-Vehn and Murakami[7]].

Inserting the values of the numerical constants for Au,[3] we have

$$\eta_x(t) = 1 - 280N^{0.68}[Rr_0^{1.52}]^{1.32}\frac{(\hat{W}L^{-2})^{0.32}}{\hat{E}(t)}, \tag{3}$$

where $\hat{E} = E/(1\text{ MJ})$, $\hat{W} = W/(10^{15}\text{ W})$, and $\hat{t} = (t/1\text{ ns})$, all other quantities being in cgs units.

We can include the effect of radiation emission from the cylinder's back surface by writing

$$\eta_x^l = (1 + \zeta)^{-1}\eta_x, \tag{4}$$

where η_x is now computed from Eq. (2) with $L^{1+\beta}$ replaced by $L^{1+\beta}(1 + \zeta)$.

Testing the accuracy of Eqs. (2–4) for a wide range of beam and converter parameters requires a large number of numerical simulations, which are at present being performed, and which will be reported and discussed in detail in a subsequent paper. However, we have already run a preliminary simulation campaign concerning bismuth beams and low-density gold converters, with parameters of direct relevance to ICF design, and have shown satisfactory agreement with the model predictions. In particular, we have taken as a reference the case of Figure 1 (with $r_0 = 0.1$ cm, $\rho_0 = 0.5$ g/cm^3, $\langle P \rangle = 3 \times 10^{16}$ W/g, and $\mathscr{E} = 10$ GeV). We have then considered:

a) cases with the reference values of ρ_0 and $\langle P \rangle$, but with different values of r_0 (in the range $1.0 \leqslant r_0 \leqslant 0.4$ cm) and/or of $\mathscr{E}$($\mathscr{E} = 10$ GeV and $\mathscr{E} = 20$ GeV);

b) cases with the reference values of r_0 and $\mathscr{E}$, but with different values of ρ_0 (in the range $0.25 \leqslant \rho_0 \leqslant 1$ g/cm^3) and/or of $\langle P \rangle$ (in the range of $3 \times 10^{15} \leqslant \langle P \rangle \leqslant 3 \times 10^{16}$ W/g);

c) cases with the reference values of r_0, ρ_0 and $\langle P \rangle$, but with different ion energy ($\mathscr{E} = 4$ GeV and $\mathscr{E} = 20$ GeV);

d) cases with the reference values of ρ_0 and $\mathscr{E}$, but with $r_0 = 0.15$ cm, and different values of $\langle P \rangle$ (again in the range $3 \times 10^{15} \leqslant \langle P \rangle \leqslant 3 \times 10^{16}$ W/g).

In all cases the converter length is $L = R/\rho_0$, and a terminal plug is included; also, we always have $r_0 < L/2$. We expect Eqs. (2–4) to apply for times t sufficiently large for the ion deposition to occur over the whole length of the cylinder (see Figure 1); for the problems studied here this always occurs for $t = 10$ ns (but not always for shorter times, e.g., $t = 5$ ns). Therefore for each problem we have plotted in Figure 4 the conversion efficiency η_x^l at $t = 10$ ns (from the 2-D simulations) versus that predicted by Eqs. (4) and (3). It appears that, in the considered range of beam-converter parameters, the simulation results and the theoretical predictions are in good agreement. This supports the use of Eqs. (2) and (4) in models of ICF target gain[8].

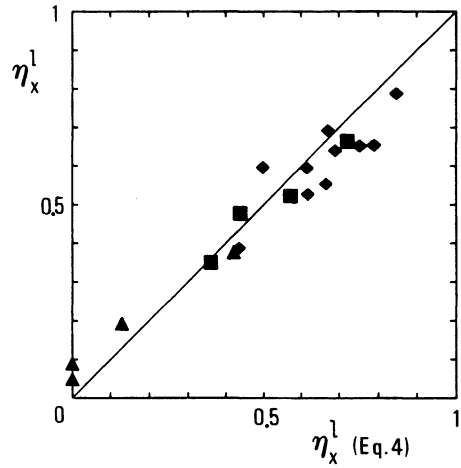

FIGURE 4 Conversion efficiency η_x^l from the 2-D simulations versus that predicted by Eqs. (2) and (4). The symbols indicate the average specific power, with the same meaning as in Figure 3.

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