Analytic models of high-temperature hohlraums

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A unified set of high-temperature-hohlraum models has been developed. For a simple hohlraum, $P_S=[A_S+(1-\alpha_W)A_W+A_H]\sigma T_R^4+(4V\sigma/c)(dT_R^4/dt)$, where P_S is the total power radiated by the source, A_S is the source area, A_W is the area of the cavity wall excluding the source and holes in the wall, A_H is the area of the holes, σ is the Stefan-Boltzmann constant, T_R is the radiation brightness temperature, V is the hohlraum volume, and c is the speed of light. The wall albedo $\alpha_W\equiv(T_W/T_R)^4$ where T_W is the brightness temperature of area A_W. The net power radiated by the source $P_N=P_S-A_S\sigma T_R^4$, which suggests that for laser-driven hohlraums the conversion efficiency η_{CE} be defined as P_N/P_{Laser}. The characteristic time required to change T_R^4 in response to a change in P_N is $4V/c[(1-\alpha_W)A_W+A_H]$. Using this model, T_R, α_W, and η_{CE} can be expressed in terms of quantities directly measurable in a hohlraum experiment. For a steady-state hohlraum that encloses a convex capsule, $P_N=\{(1-\alpha_W)A_W+A_H+[(1-\alpha_C)A_C(A_S+\alpha_W A_W)/A_T]\}\sigma T_{\mathrm{RC}}^4$, where α_C is the capsule albedo, A_C is the capsule area, $A_T\equiv(A_S+A_W+A_H)$, and T_{RC} is the brightness temperature of the radiation that drives the capsule. According to this relation, the capsule-coupling efficiency of the baseline National Ignition Facility hohlraum is 15–23 % higher than predicted by previous analytic expressions. A model of a hohlraum that encloses a z pinch is also presented.

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I. INTRODUCTION

High-temperature hohlraums are being used for indirect-drive inertial-confinement-fusion (ICF), high-energy-density, equation-of-state, and astrophysics research [1–83]. Laser-driven-hohlraum experiments have been conducted at 100–300 eV [2,4–8,10–13,15–23,25–28,30,31,36,37,39,44,49, 52,53,72,75,77]. National Ignition Facility (NIF) hohlraums will be driven by 400 TW of laser power, and are expected to reach 300 eV in systems designed to achieve thermonuclear ignition [29,34,36,41,48,51,52,64,80]. Temperatures of 60–180 eV have been produced in z-pinch-driven cavities [16,42,44,46,54,62,65,66,70,71,74,78,79,81,82]. A 60-MA z-pinch driver would achieve 210–300 eV [63,65,67,70]. Megajoule heavy-ion beams focused to spots a few millimeters in diameter would drive hohlraums to 200–300 eV [14,24,33,43,50,52,55–59,76].

Radiation-hydrodynamic simulations must be performed to characterize high-temperature hohlraums accurately. Nevertheless, it is convenient to obtain analytic estimates of hohlraum temperatures, both for existing systems and configurations proposed for future facilities. Useful steady-state power-balance models (sometimes expressed in terms of energy) have been developed and are commonly used for zero-dimensional calculations [1,6,8,10,11,14,15,20,25,30,36,37, 44,52,63,68,69,81,83].

In Sec. II we develop a time-dependent model and quantify the error introduced by the steady-state approximation. The model does not assume the source area is negligible, and distinguishes between the radiation, wall, and source brightness temperature. For a laser-driven hohlraum the model leads to a definition of laser-conversion efficiency in terms of the net source power. In Sec. III we use the model to express the radiation brightness temperature, wall albedo, and (for a laser-driven system) laser-conversion efficiency in terms of directly-measurable quantities. (The measurements can, for example, be made with a power-imaging diagnostic as described by Olson *et al.* [84].) We also show how, in certain situations, the radiation temperature can be obtained from a single x-ray-power measurement, as described by Decker and co-workers [39]. In Sec. IV, following ideas developed by Murakami and Meyer-ter-Vehn [14], we generalize the model to include a convex inertial-confinement-fusion capsule. The expressions obtained for the brightness temperature of the radiation that drives the capsule, and the capsule-coupling efficiency, take into account the anisotropic radiation flux and source and hole areas self-consistently. In Sec. V we model a cavity that encloses a centrally-located convex source, such as a z pinch. The models in these sections describe single cavities, and can be applied to a system of connected cavities as described by Tsakiris *et al.* [11], Rosen [20,36], Hammer *et al.* [63], and Cuneo *et al.* [81].

The models outlined in Secs. II, IV, and V must be supplemented with additional information to determine the wall albedo, source power, and radiation temperatures. Analytic expressions for the albedo have been developed by Rosen *et al.* [1,20,30,36,52,69,85] and Pakula, Sigel and co-workers [3,6,10,15,19,85,86]. The source power might best be obtained from measurements or numerical simulations. For a z-pinch-driven hohlraum, we can estimate the source power from measurements using a partially open geometry, as described in Sec. VI. In Sec. VII we comment briefly on NIF and Z-accelerator hohlraum designs.

II. SIMPLE HOHLRAUM

We consider first an idealized radiation cavity with volume V driven by an x-ray source. We assume the total area A_T of the surface that encloses V is equal to $A_S+A_H+A_W$, where A_S is the source area, A_H is the area of holes in the hohlraum wall, and A_W is the area of the wall excluding the source and holes. This is valid when the source region can be characterized by an area A_S that is part of A_T, and does not apply, for example, when a significant fraction of the source x rays are emitted by a plasma that fills V. When the source is not located inside the hohlraum, A_S is the area of the aperture through which the x-ray-source radiation enters. A_H includes the area of diagnostic apertures in the hohlraum wall, and for a laser-driven hohlraum, the laser entrance holes.

We assume areas A_S and A_H are uniformly distributed across A_T, radiation entering the cavity from areas A_S and A_W is Lambertian, and no radiation enters the cavity through A_H. We define U_R to be the energy in radiation that fills V and assume the radiation is homogeneous and isotropic. Under these conditions it is straightforward to show that the radiation flux incident on A_T is equal to $(cU_R/4V)$, independent of the spectrum, where c is the speed of light [87,88]. Hence the radiation brightness temperature T_R is given by

$$\sigma T_R^4 = \frac{cU_R}{4V}, \tag{1}$$

where σ is the Stefan-Boltzmann constant. (Equations are in mks units throughout.)

Equating dU_R/dt to the difference between the incoming and outgoing power at the surface defined by A_T gives

$$\frac{dU_R}{dt} = (P_S + P_W) - (A_S + A_W + A_H)\sigma T_R^4, \tag{2}$$

where P_S is the total power entering the cavity from area A_S, and P_W is the total power entering the cavity from area A_W. (No assumptions have been made, of course, about the absorptivities of areas A_S and A_W.) Equation (2) assumes that either the hohlraum is evacuated, or if it is filled with plasma, that the power required to heat the plasma is much less than dU_R/dt. The above equation also assumes PdV work due to motion of the cavity wall can be neglected. The brightness temperatures T_S and T_W of areas A_S and A_W, respectively, are obtained from

$$\sigma T_S^4 = \frac{P_S}{A_S} \quad \text{and} \quad \sigma T_W^4 = \frac{P_W}{A_W}. \tag{3}$$

Equations (1)–(3) can be rewritten as

$$P_S = [A_S + (1-\alpha_W)A_W + A_H]\sigma T_R^4 + \frac{4V\sigma}{c}\frac{dT_R^4}{dt}, \tag{4}$$

where α_W, the wall albedo, is defined by

$$\alpha_W \equiv \frac{P_W}{A_W \sigma T_R^4} = \left(\frac{T_W}{T_R}\right)^4. \tag{5}$$

P_W is the sum of the incident hohlraum-radiation power reflected from the area A_W and the power reemitted. (A fraction of the power incident on A_W is reflected due to scattering and plasma collective effects. The rest is absorbed, some of which is subsequently reemitted. The reflected component is, of course, always less than the instantaneous incident power. The reemitted component can be greater, such as during times when the area A_W is cooling.) For most experiments of interest, very little of the incident radiation is reflected. Hence the quantity α_W might more correctly be referred to as the reemission coefficient [6].

Since the value of α_W at time t is a functional of $T_R(t)$ over the time interval $(-\infty, t)$ [1,3,6,10,15,19,20,30,36,52,69,85,86], Eq. (4) is, in general, nonlinear. However, in many situations there are periods of interest over which the quantity $[A_S + (1-\alpha_W)A_W + A_H]$ does not change significantly. During such times we can define a hohlraum time constant τ_H as the characteristic time required to change T_R^4 in response to a change in P_S:

$$\tau_H \equiv \frac{4V}{c[A_S + (1-\alpha_W)A_W + A_H]}. \tag{6}$$

We note τ_H increases as the hohlraum becomes more efficient, i.e., as $[(1-\alpha_W)A_W + A_H] \to 0$.

Equation (6) is valid for volumes with arbitrary shape, and takes into account the source and hole areas. The time constant implicit in Eq. 4.20 of Ref. [8] is $-4R/3c(\ln \alpha_W)$, where it is assumed the cavity is spherical, the cavity radius$=R$, and the source and hole areas can be neglected. Equation 6 reduces to this expression when $V = 4\pi R^3/3$, $A_W = 4\pi R^2$, $A_S = A_H = 0$, and $0 < (1-\alpha_W) \ll 1$.

Since the hohlraum-radiation power incident on A_S is $A_S \sigma T_R^4$, the net power entering the cavity through A_S is

$$P_N = P_S - A_S \sigma T_R^4. \tag{7}$$

Combining Eqs. (4) and (7) gives

$$P_N = [(1-\alpha_W)A_W + A_H]\sigma T_R^4 + \frac{4V\sigma}{c}\frac{dT_R^4}{dt}. \tag{8}$$

Over time periods when $[(1-\alpha_W)A_W + A_H]$ does not change significantly, the characteristic time required to change T_R^4 in response to a change in P_N is

$$\tau_{\rm HN} \equiv \frac{4V}{c[(1-\alpha_W)A_W + A_H]}. \tag{9}$$

In the steady state (when $dU_R/dt = 0$) Eqs. (7) and (8) become

$$P_S - A_S \sigma T_R^4 = P_N = [(1-\alpha_W)A_W + A_H]\sigma T_R^4. \tag{10}$$

The above equation suggests that if A_T and A_H are held constant and P_N is independent of A_S, then T_R is maximized when $A_S = A_T - A_H$ and $A_W = 0$. If P_N is not independent of A_S, there may be a different value of A_S that maximizes T_R. We note also that as $[(1-\alpha_W)A_W + A_H] \to 0$, i.e., as the hohlraum becomes increasingly efficient, $T_R \to T_S$, the brightness temperature of the source.

Equation (10) is similar, but not identical, to previous expressions of the steady-state power balance for a zero-dimensional hohlraum. Some of the earlier discussions define A_W to include the source area, which is equivalent to assuming $A_S = 0$ and T_S is infinite. In some discussions the source term is a net power not defined as in Eq. (10); in others, it is not clear whether the net or total source power is intended. Some discussions use T_R and T_W interchangeably. However, for most situations of current interest Eq. (10) is consistent to first order with previous expressions.

For a laser-driven hohlraum the source term commonly used is $\eta_{\mathrm{CE}}P_{\mathrm{Laser}}$, where η_{CE} is the instantaneous conversion efficiency from laser to x-ray power. We propose η_{CE} be defined as

$$\eta_{\mathrm{CE}} \equiv \frac{P_N}{P_{\mathrm{Laser}}} = \frac{P_S - A_S\sigma T_R^4}{P_{\mathrm{Laser}}}, \tag{11}$$

which is the conversion efficiency of laser light to x-ray-source power that exceeds the hohlraum-radiation power incident on the source. In an open geometry $\eta_{\mathrm{CE}} = P_N/P_{\mathrm{Laser}} = P_S/P_{\mathrm{Laser}}$.

Since Eq. (10) is more convenient than Eq. (8), it is useful to estimate the error due to the assumption dU_R/dt can be neglected. We define $(1-\delta)$ to be the ratio of T_R^4 as determined by Eq. (8), to T_R^4 as determined by Eq. (10), where δ is the fractional error. When P_N and $[(1-\alpha_W)A_W + A_H]$ do not change significantly over a time interval that we define as extending from 0 to *t*, we estimate from Eq. (8):

$$T_R^4 = \frac{P_N}{\sigma[(1-\alpha_W)A_W + A_H]}\left[1 - \exp\left(-\frac{t}{\tau_{\mathrm{HN}}}\right)\right] \tag{12}$$

assuming $T_R^4(t) \gg T_R^4(t=0)$. From Eqs. (10) and (12) we obtain

$$\delta = \exp\left(-\frac{t}{\tau_{\mathrm{HN}}}\right), \tag{13}$$

which equals 5% when $t \approx 3\tau_{\mathrm{HN}}$.

When $P_N \propto t^{4n}$ over the time interval from 0 to *t* where $4n$ is a positive integer, $[(1-\alpha_W)A_W + A_H]$ does not change significantly over this interval, and $t \ll \tau_{\mathrm{HN}}$, we find from Eq. (8):

$$T_R^4 \approx \frac{P_N}{\sigma[(1-\alpha_W)A_W + A_H]}\left[\frac{t}{(4n+1)\tau_{\mathrm{HN}}}\right], \tag{14}$$

assuming $T_R^4(t) \gg T_R^4(t=0)$. From Eqs. (10) and (14) we obtain

$$\delta \approx 1 - \left[\frac{t}{(4n+1)\tau_{\mathrm{HN}}}\right]. \tag{15}$$

When $t \gg 4n\tau_{\mathrm{HN}}$,

$$T_R^4 \approx \frac{P_N}{\sigma[(1-\alpha_W)A_W + A_H]}\left[1 - \left(\frac{4n}{t/\tau_{\mathrm{HN}}}\right)\right] \tag{16}$$

$$\delta \approx \frac{4n}{t/\tau_{\mathrm{HN}}}. \tag{17}$$

When $P_N \propto t^4$ (and T_R is approximately proportional to *t*), $\delta = 5\%$ when $t \approx 80\tau_{\mathrm{HN}}$.

Equations (12)–(17), of course, only estimate time-dependent effects since they neglect the dependence of α_W on the radiation-temperature history. These equations are expressed in terms of P_N and τ_{HN}; similar expressions can be readily obtained in terms of P_S and τ_H.

III. T_R, α_W, AND η_{CE} AS FUNCTIONS OF DIRECTLY MEASURABLE QUANTITIES

The results of the previous section can be used to suggest methods for making time-resolved measurements of T_R, α_W, and η_{CE}. Combining Eqs. (1) and (2) we find

$$A_T\sigma[T_T^4 - T_R^4] = \frac{4V\sigma}{c}\frac{dT_R^4}{dt} = \frac{dU_R}{dt}, \tag{18}$$

where $T_T \equiv [(P_S + P_W)/A_T\sigma]^{1/4}$ is the brightness temperature of the total wall area A_T. Hence dU_R/dt is equal to the difference between $A_T\sigma T_T^4$ (the total power emitted by A_T) and $A_T\sigma T_R^4$ (the total power incident on A_T).

When $t \gg (4V/A_T c)$ (i.e., when $dU_R/dt \approx 0$) Eqs. (3) and (18) can be combined to give:

$$\sigma T_R^4 = \sigma T_T^4 = f_S\sigma T_S^4 + f_W\sigma T_W^4, \tag{19}$$

where $f_S \equiv (A_S/A_T)$ and $f_W \equiv (A_W/A_T)$. In the steady state, the radiation brightness temperature equals the brightness temperature of A_T, and T_R^4 is a linear combination of T_S^4 and T_W^4.

Equations (10) and (19) are equivalent; however, Eq. (19) gives $T_R(t)$ as a function of f_S, f_W, T_S, and T_W, quantities that can be directly measured as a function of time in a hohlraum experiment [84,89–108]. Such a measurement of T_R might complement, for example, the use of a shock-breakout diagnostic, which requires radiation-hydrodynamic simulations to infer T_R [44,84,97]. Obtaining T_R is of interest since it is the brightness temperature of the radiation that would drive a physics package placed inside the hohlraum.

Results by Decker *et al.* [39] and Eq. (19) suggest that a single x-ray power measurement can be used to obtain $T_R(t)$. As described in [39], we consider an x-ray-flux diagnostic that views the hohlraum wall, with part of the source and no holes in the field of view. We define v_S to be the fraction of the detector's field of view occupied by the source, and $v_W \equiv 1 - v_S$. If the diagnostic is designed such that $v_S = [A_S/(A_S + A_W)]$ and $v_W = [A_W/(A_S + A_W)]$, we have from Eq. (19)

$$\sigma T_R^4 = \frac{A_S + A_W}{A_T}[v_S\sigma T_S^4 + v_W\sigma T_W^4] = (f_S + f_W)\left(\frac{P_{\mathrm{View}}}{A_{\mathrm{View}}}\right), \tag{20}$$

where $P_{\mathrm{View}} \equiv A_{\mathrm{View}}(v_S\sigma T_S^4 + v_W\sigma T_W^4)$ is the total power emitted by the field of view and A_{View} is its area. In such an arrangement the measured flux $(P_{\mathrm{View}}/A_{\mathrm{View}})$ would be directly proportional to T_R^4. Using this technique to measure $T_R(t)$ is, of course, meaningful only if f_S and f_W are known and do not change significantly during the period of interest.

Combining Eqs. (5) and (19) gives the wall albedo:

$$\alpha_W = \frac{1}{f_S\left(\frac{T_S}{T_W}\right)^4 + f_W}. \tag{21}$$

Hence $\alpha_W(t)$ inside a hohlraum can be determined from time-resolved measurements of f_S, f_W, and $(T_S/T_W)^4$. It has been proposed [35,47,76,80] that optimized wall-material mixtures be used to increase albedos: Eq. (21) suggests one technique for testing such mixtures inside a hohlraum.

Since Eq. (21) implicitly assumes the net power is as defined by Eq. (7), and distinguishes between the wall and radiation temperatures, it differs from a similar expression for the albedo given as Eq. 8.4 in Ref. [52]:

$$\alpha_W = \frac{1}{\left(\frac{f_S}{f_W}\right)\left(\frac{T_S}{T_W}\right)^4 + \left(2 - \frac{1}{f_W}\right)}. \tag{22}$$

However, Eqs. (21) and (22) are approximately equivalent when $f_W \approx 1$.

For a laser-driven hohlraum, combining Eqs. (3), (11), and (19) gives the conversion efficiency:

$$\eta_{\mathrm{CE}} = \frac{f_S A_T}{P_{\mathrm{Laser}}}[(1-f_S)\sigma T_S^4 - f_W \sigma T_W^4]. \tag{23}$$

Consequently we can determine $\eta_{\mathrm{CE}}(t)$ inside a hohlraum from time-resolved measurements of f_S, f_W, T_S^4, and T_W^4.

The quantities f_S, f_W, T_S^4, T_W^4, and $(T_S/T_W)^4$ might be obtained from an x-ray-framing camera [95] and a filtered array of x-ray detectors, as described in [65,84]. According to Eqs. (19), (21), and (23), such a system could in principle provide $T_R(t)$, $\alpha_W(t)$, and $\eta_{\mathrm{CE}}(t)$ using a single aperture in the hohlraum wall. When f_S and f_W are known and relatively constant during the time of interest, only measurements of T_S^4 and T_W^4 would be required.

IV. HOHLRAUM WITH A CONVEX CAPSULE

A. Two radiation temperatures

1. The source directly irradiates the capsule

We now assume the hohlraum described in Secs. II and III encloses a centrally located convex capsule, such as might be used in ICF experiments. Since a convex surface cannot irradiate itself, the radiation flux incident on the capsule is, in general, not the same as the flux incident on the rest of the cavity wall [14,109]. We also assume the source is allowed to irradiate the capsule directly, and is not blocked by shields to improve radiation symmetry. This applies, for example, to proposed NIF ignition hohlraums [29,34,36,41,48,51,52, 64,80], distributed-radiator heavy-ion-beam-driven hohlraums [57–59,76], and the central cavity in the *z*-pinch-driven system described by Hammer and co-workers [63,65,81,82].

As in Secs. II and III, we assume the area of the outer hohlraum wall A_T equals $(A_S + A_W + A_H)$, areas A_S and A_H are uniformly distributed across A_T, and radiation entering the cavity from areas A_S and A_W is Lambertian. We define σT_R^4 to be the radiation flux incident on A_T, and σT_{RC}^4 to be the flux incident on the capsule area A_C. We assume σT_R^4 and σT_{RC}^4 are uniform on areas A_T and A_C, respectively.

Under these conditions Eq. (4) becomes (neglecting dU_R/dt)

$$P_S = [A_S + (1-\alpha_W)A_W + A_H]\sigma T_R^4 + (1-\alpha_C)A_C \sigma T_{\mathrm{RC}}^4, \tag{24}$$

where

$$\alpha_W \equiv \frac{P_W}{A_W \sigma T_R^4} \quad \alpha_C \equiv \frac{P_C}{A_C \sigma T_{\mathrm{RC}}^4} \tag{25}$$

and P_C is the total power emitted from the area A_C.

Since the capsule is convex, σT_{RC}^4 is equal to the flux emitted by the area A_T [14,109]:

$$\sigma T_{\mathrm{RC}}^4 = \frac{P_S + P_W}{A_S + A_W + A_H} = \frac{P_S + \alpha_W A_W \sigma T_R^4}{A_T}. \tag{26}$$

Combining Eqs. (7), (24), and (26) gives

$$P_S = \left[A_S + (1-\alpha_W)A_W + A_H + (1-\alpha_C)A_C\left(\frac{\alpha_W A_W}{A_T}\right)\right]\sigma T_{\mathrm{RC}}^4 \tag{27}$$

and

$$P_N = \left[(1-\alpha_W)A_W + A_H + (1-\alpha_C)A_C\left(\frac{A_S + \alpha_W A_W}{A_T}\right)\right]\sigma T_{\mathrm{RC}}^4. \tag{28}$$

Similar expressions for P_S and P_N can be obtained as functions of T_R. From Eq. (28) we obtain the coupling efficiency η_{Capsule} of P_N to the power absorbed by the capsule:

$$\begin{aligned}\eta_{\mathrm{Capsule}} &\equiv \frac{(1-\alpha_C)A_C \sigma T_{\mathrm{RC}}^4}{P_N} \\ &= \left[\frac{(1-\alpha_W)A_W}{(1-\alpha_C)A_C} + \frac{A_H}{(1-\alpha_C)A_C} + \left(\frac{A_S + \alpha_W A_W}{A_T}\right)\right]^{-1}.\end{aligned} \tag{29}$$

As $\alpha_C \to 0$ and $A_C \to A_T$, then $\eta_{\mathrm{Capsule}} \to 1$, as expected.

Since Eqs. (27)–(29) account for the source area, hole area, and anisotropic radiation flux in a self-consistent manner, they differ from previous expressions for the radiation drive and capsule-coupling efficiency [36,52]. (For example, the expression for the coupling efficiency given as Eq. 7.37 in Ref. [52] is derived from Eqs. 7.30 and 7.36. Equation 7.30 assumes there are holes in the hohlraum wall whereas Eq. 7.36 does not; in addition, Eq. 7.36 assumes the source does not directly irradiate the capsule, and that the source area is negligible. However, Eq. 7.37 agrees approximately with Eq. (29) above when A_S, $A_H \ll A_T$ and $\alpha_W \approx 1$.)

The expression for the coupling efficiency given as Eq. 3.9 in Ref. [14] assumes that the source and holes area can be neglected. If we assume (using the notation of Ref. [14]) that $P_{S1}=A_1P_S/A_2$; i.e., that the source is uniformly distributed across the cavity wall and is allowed to irradiate the capsule directly, then this expression becomes identical to Eq. (29) above when $A_S=A_H=0$.

2. The source indirectly radiates the capsule

In some ICF concepts involving heavy-ion beams or z pinches, direct radiation from sources located at both ends of a cylindrical hohlraum is blocked from the capsule by polar x-ray symmetrization shields [14,33,50,55,56,65,67]. (Such shields would, of course, also prevent the sources from receiving direct radiation from the capsule.) For such a system we define A_W to include the surface area of the shields. In addition, we make the simplifying assumptions that the radiation flux incident on the sources is the same as that on the capsule, and the sources and capsule are directly irradiated only by power emitted from the region defined by A_W.

We define σT_{RC}^4 to be the flux incident on A_C and A_S, σT_R^4 the flux incident on the area (A_W+A_H), and assume the fluxes are uniform over the respective areas. Under these conditions Eqs. (24) and (26) become

$$P_S=A_S\sigma T_{\mathrm{RC}}^4+[(1-\alpha_W)A_W+A_H]\sigma T_R^4+(1-\alpha_C)A_C\sigma T_{\mathrm{RC}}^4, \tag{30}$$

$$\sigma T_{\mathrm{RC}}^4=\frac{P_W}{A_W+A_H}=\frac{\alpha_W A_W\sigma T_R^4}{A_W+A_H}. \tag{31}$$

Combining Eqs. (30) and (31) gives

$$\begin{aligned}P_S-A_S\sigma T_{\mathrm{RC}}^4&=P_N\\&=\left[\left(\frac{[(1-\alpha_W)A_W+A_H](A_W+A_H)}{\alpha_W A_W}\right)\right.\\&\quad\left.+(1-\alpha_C)A_C\right]\sigma T_{\mathrm{RC}}^4.\end{aligned} \tag{32}$$

The capsule coupling efficiency is:

$$\begin{aligned}\eta_{\mathrm{Capsule}}&\equiv\frac{(1-\alpha_C)A_C\sigma T_{\mathrm{RC}}^4}{P_N}\\&=\left[\left(\frac{[(1-\alpha_W)A_W+A_H](A_W+A_H)}{\alpha_W A_W(1-\alpha_C)A_C}\right)+1\right]^{-1}.\end{aligned} \tag{33}$$

As $\alpha_C\to 0$ and $A_C\to(A_W+A_H)$, then $\eta_{\mathrm{Capsule}}\to\alpha_W A_W/(A_W+A_H)$, as expected.

As noted previously, the expression for the coupling efficiency given as Eq. 3.9 in Ref. [14] assumes that the source and hole areas are negligible; in addition, it neglects the area of the shields. If we assume (using the notation of Ref. [14]) that $P_{S1}=0$; i.e., that the sources are not allowed to irradiate the capsule directly, this expression becomes identical to Eq. (33) above when the shield area, A_S, and $A_H=0$.

B. Single radiation temperature

Time-dependent effects are most readily estimated with a simpler, though less-accurate, single-radiation-temperature model. If we neglect that the capsule is convex and assume that the source irradiates the capsule directly, then $T_{\mathrm{RC}}=T_R$, and we can generalize the arguments in Sec. II to obtain

$$\begin{aligned}P_S-A_S\sigma T_R^4&=P_N\\&=[(1-\alpha_W)A_W+A_H+(1-\alpha_C)A_C]\sigma T_R^4\\&\quad+\frac{4V\sigma}{c}\frac{dT_R^4}{dt}.\end{aligned} \tag{34}$$

Equations (27) and (28) are consistent with Eq. (34) when $A_C\to 0$, since in this limit the flux incident on A_T approaches the flux emitted, and $T_R\to T_{\mathrm{RC}}$.

The hohlraum time constants become

$$\tau_H\equiv\frac{4V}{c[A_S+(1-\alpha_W)A_W+A_H+(1-\alpha_C)A_C]}, \tag{35}$$

$$\tau_{\mathrm{HN}}\equiv\frac{4V}{c[(1-\alpha_W)A_W+A_H+(1-\alpha_C)A_C]}, \tag{36}$$

which are meaningful only over time periods during which τ_H and τ_{HN} do not change significantly. Other results obtained in Sec. II follow immediately.

Assuming Eq. (34) and that dU_R/dt can be neglected, the capsule-coupling efficiency can be expressed as:

$$\begin{aligned}\eta_{\mathrm{Capsule}}&\equiv\frac{(1-\alpha_C)A_C\sigma T_R^4}{P_N}\\&=\left[\frac{(1-\alpha_W)A_W}{(1-\alpha_C)A_C}+\frac{A_H}{(1-\alpha_C)A_C}+1\right]^{-1}.\end{aligned} \tag{37}$$

As $A_H\to 0$ and $\alpha_W\to 1$, the efficiencies given by Eqs. (29), (33), and (37) approach 1, since in this limit the only net absorber of power in the hohlraum is the capsule.

V. HOHLRAUM WITH A CONVEX SOURCE

A. Two radiation temperatures

The models in Secs. II, III, IV A 1, and IV B assume that A_S is uniformly distributed across A_T, and that the source radiates onto itself. If we assume instead that the source is convex, then the source cannot irradiate itself, and the radiation flux incident on the source is, in general, not the same as the flux incident on the rest of the cavity wall [14,109].

This approximates a hohlraum that encloses a z pinch, as is used in some weapon-physics and ICF experiments [42,44,54,61–63,65,71,74,81,82]. We shall assume that the results of this section are relevant primarily to such a system.

We assume the area of the outer hohlraum wall equals $(A_W+A_H+A_G)$, where A_G is the area of the transmission-line gap that feeds power to the pinch. We assume radiation entering the cavity through areas A_W and A_G is Lambertian. We define σT_{RS}^4 to be the radiation flux incident on A_S, and σT_R^4 to be the flux incident on the area $(A_W+A_H+A_G)$. We assume σT_{RS}^4 and σT_R^4 are uniform on areas A_S and $(A_W+A_H+A_G)$, respectively.

Under these assumptions Eq. (4) becomes (neglecting dU_R/dt)

$$P_S=A_S\sigma T_{\mathrm{RS}}^4+[(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G]\sigma T_R^4, \tag{38}$$

where

$$\alpha_W\equiv\frac{P_W}{A_W\sigma T_R^4}\quad \alpha_G\equiv\frac{P_G}{A_G\sigma T_R^4}. \tag{39}$$

α_G, the effective albedo of area A_G, is not zero because some of the radiation reemitted from the walls of the transmission line enters the hohlraum [61,71,81]. P_G is the total power that enters the hohlraum through area A_G.

Since the source is convex, σT_{RS}^4 is equal to the flux emitted by the region defined by the area $(A_W+A_H+A_G)$ [14,109]:

$$\sigma T_{\mathrm{RS}}^4=\frac{P_W+P_G}{A_W+A_H+A_G}=\frac{(\alpha_W A_W+\alpha_G A_G)\sigma T_R^4}{A_W+A_H+A_G}. \tag{40}$$

Combining Eqs. (38) and (40) gives

$$P_S=\left[\left(\frac{\alpha_W A_W+\alpha_G A_G}{A_W+A_H+A_G}\right)A_S+(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G\right]\sigma T_R^4. \tag{41}$$

Since $P_N=P_S-A_S\sigma T_{\mathrm{RS}}^4$, we have from Eq. (38):

$$P_N=[(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G]\sigma T_R^4. \tag{42}$$

Similar expressions for P_S and P_N can be obtained as functions of T_{RS}.

B. Single radiation temperature

If we neglect that the source is convex and assume $T_{\mathrm{RS}}=T_R$, we can generalize the arguments in Sec. II to obtain a single-radiation-temperature model of a hohlraum containing a z pinch:

$$\begin{aligned}P_S-A_S\sigma T_R^4&=P_N\\&=[(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G]\sigma T_R^4\\&\quad+\frac{4V\sigma}{c}\frac{dT_R^4}{dt}.\end{aligned} \tag{43}$$

Equations (41) and (42) are consistent with Eq. (43) when A_H, $A_G\ll A_W$ and $\alpha_W\approx1$, since in this limit the flux incident on $(A_W+A_H+A_G)$ approaches the flux emitted by this area, and $T_R\rightarrow T_{\mathrm{RS}}$.

The hohlraum time constants become

$$\tau_H\equiv\frac{4V}{c[A_S+(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G]}, \tag{44}$$

$$\tau_{\mathrm{HN}}\equiv\frac{4V}{c[(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G]}. \tag{45}$$

Of course, Eqs. (44) and (45) have meaning only over time periods during which τ_H and τ_{HN} do not change significantly. Other results obtained in Sec. II follow immediately.

VI. *z*-PINCH-SOURCE MODEL

A. P_S as a function of geometry

In principle, P_S can be measured through a small diagnostic hole in the hohlraum wall. Because of aperture closure it is more convenient to measure the source power in a system with large diagnostic apertures. However, large apertures lower the radiation temperature in a hohlraum, which decreases the heating of the source and hence the source temperature and total source power P_S. For a z-pinch source, a simple model can be used to estimate the effect of hohlraum geometry on P_S.

We consider a z pinch at stagnation and model it as a convex blackbody with constant volume. We estimate the time rate of change of the pinch's internal energy U_S as

$$\frac{dU_S}{dt}=P_{\mathrm{Ext}}+A_S\sigma T_{\mathrm{RS}}^4-P_S=P_{\mathrm{Ext}}-P_N, \tag{46}$$

where P_{Ext} is the external source of power delivered to the pinch, and σT_{RS}^4 is the radiation flux incident on the pinch. In a geometry with large diagnostic apertures,

$$\frac{dU_{\mathrm{SL}}}{dt}=P_{\mathrm{Ext}}+A_S\sigma T_{\mathrm{RSL}}^4-P_{\mathrm{SL}}=P_{\mathrm{Ext}}-P_{\mathrm{NL}}, \tag{47}$$

where the subscript ''L'' denotes quantities in the large-aperture system. (We assume P_{Ext} and A_S are independent of geometry.) When dU_R/dt, dU_S/dt, and dU_{SL}/dt can be neglected, we can combine Eqs. (41), (42), (46), and (47) to obtain

$$gP_S=P_N=P_{\mathrm{NL}}=g_L P_{\mathrm{SL}}, \tag{48}$$

where

$$g\equiv\frac{(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G}{\left(\frac{\alpha_W A_W+\alpha_G A_G}{A_W+A_H+A_G}\right)A_S+(1-\alpha_W)A_W+A_H+(1-\alpha_G)A_G} \tag{49}$$

is calculated for the hohlraum without the large diagnostic apertures, and g_L is the corresponding quantity for the large-aperture system.

Equation (48) gives the total- and net-source terms P_S and P_N as a function of $P_{\rm SL}$, the total source power in the system with large apertures. According to Eq. (48), the total power P_S emitted by a z pinch in the hohlraum without the large apertures is greater than $P_{\rm SL}$ by the factor (g_L/g).

B. Source time constant

Equation (48) assumes dU_R/dt, dU_S/dt, and $dU_{\rm SL}/dt$ can be neglected. We can assume $dU_R/dt=0$ when the time of interest is much longer than the hohlraum time constant, i.e., the time required to fill the hohlraum with radiation. We can set $dU_S/dt=dU_{\rm SL}/dt=0$ when the time of interest is much longer than the time required by the radiation to heat the z-pinch source to its equilibrium temperature.

An estimate of the hohlraum time constant is given as Eq. (45). To estimate the z-pinch-source time constant, we make the simplifying assumption that the hohlraum time constant can be neglected, and set $dU_R/dt=0$. Combining Eqs. (41), (42), (46), and (47) we obtain

$$\frac{dU_S}{dt}-\frac{dU_{\rm SL}}{dt}=P_{\rm NL}-P_N=g_L P_{\rm SL}-gP_S. \tag{50}$$

To develop an expression for U_S, we assume the z pinch can be modeled as an isothermal plasma with ion-charge state $Z\gg 1$, and that U_S is dominated by the kinetic energy of the electrons and potential energy of the ions [110]. Hence

$$U_S=\tfrac{3}{2}NZkT_S+N\sum_{j=1}^{Z}I_j=\tfrac{3}{2}NZkT_S+NZI_{\rm Ave}=(0.07)NkT_S^{3/2}$$
$$\equiv\beta T_S^{3/2}, \tag{51}$$

where N is the number of ions, k is the Boltzmann constant, I_J is the jth ionization potential, and $I_{\rm Ave}$ is the average of the first Z ionization potentials. Equation (51) sets $Z=(0.02)T_S^{1/2}$ and $I_{\rm Ave}=2kT_S$ (T_S in degrees kelvin), which are reasonable approximations for a tungsten z pinch at electron densities ($2\times 10^{28}\,{\rm m}^{-3}$) and temperatures ($2\times 10^6$ K) of interest [24,86,111–114]. Similarly, $U_{\rm SL}=\beta T_{\rm SL}^{3/2}$.

Combining these expressions for internal energy with Eqs. (3) and (50) (and assuming $A_S=A_{\rm SL}$) gives

$$\tfrac{3}{2}\beta\left(T_S^{1/2}\frac{dT_S}{dt}-T_{\rm SL}^{1/2}\frac{dT_{\rm SL}}{dt}\right)=A_S\sigma(g_L T_{\rm SL}^4-gT_S^4). \tag{52}$$

Assuming $T_S^4=T_{\rm SL}^4(1+f)$ where $0\le f\ll 1$, $f(t=0)=0$, and $T_{\rm SL}=\gamma t^n$ where γ is a positive constant and n a non-negative integer, we find (neglecting terms second and higher order in f)

$$\frac{df}{dt}+\left[\left(\frac{3n}{2t}\right)+\left(\frac{8A_S\sigma g}{3\beta}\right)\gamma^{5/2}t^{5n/2}\right]f=\frac{8A_S\sigma(g_L-g)}{3\beta}\,\gamma^{5/2}t^{5n/2} \tag{53}$$

When $t\gg[3n/(5n+2)]^{2/(5n+2)}\tau_S$,

$$f(t)=\frac{g_L-g}{g}\left\{1-\exp\left[-\left(\frac{t}{\tau_S}\right)^{(5n+2)/2}\right]\right\}, \tag{54}$$

where the source time constant τ_S is defined by

$$\tau_S\equiv\left[\frac{(15n+6)\beta}{16gA_s\sigma\gamma^{5/2}}\right]^{2/(5n+2)}. \tag{55}$$

As $t\to\infty, f\to(g_L-g)/g$, $T_S^4\to T_{\rm SL}^4(g_L/g)$, and [according to Eq. (48)] $P_N\to P_{\rm NL}$.

To estimate the error due to the assumption $dU_S/dt=dU_{\rm SL}/dt=0$, we define $1-\varepsilon$ to be the ratio of P_S as determined by Eq. (50), to P_S as determined by Eq. (48). Hence the fractional error ε is given by

$$\varepsilon\equiv\frac{\left(\dfrac{g_LP_{\rm SL}}{g}\right)-P_{\rm SL}(1+f)}{\left(\dfrac{g_LP_{\rm SL}}{g}\right)}=\left(\frac{g_L-g}{g_L}\right)\exp\left[-\left(\frac{t}{\tau_S}\right)^{(5n+2)/2}\right]. \tag{56}$$

The maximum value of ε equals $(g_L-g)/g_L$ and occurs when $t=0$.

VII. NIF AND Z-ACCELERATOR HOHLRAUMS

The baseline NIF hohlraum [29,34,36,41,51,52,64] can be modeled as described in Sec. IV A 1. For this system $A_S=4.0\times 10^{-5}\,{\rm m}^2$, $A_W=1.6\times 10^{-4}\,{\rm m}^2$, $A_H=1.2\times 10^{-5}\,{\rm m}^2$, $A_C\sim 6\times 10^{-6}\,{\rm m}^2$, $\alpha_W=0.89$, $\alpha_C\sim 0$, and $V=2.3\times 10^{-7}\,{\rm m}^3$ [29,34,36,52]. Assuming a 75% laser-conversion efficiency [36] and $P_{\rm Laser}=400$ TW [29,34,52], Eqs. (11) and (28) predict that the capsule-drive temperature $T_{\rm RC}$ would be 303 eV. The value predicted by integrated calculations is 300 eV [29,34,52]. According to Eq. (29), $\eta_{\rm Capsule}=17\%$, which is 15–23 % higher than predicted by previous analytic relations [36,52]. The total source power P_S would be 640 TW, substantially in excess of $P_{\rm Laser}$.

Using Eqs. (12)–(17) and (34)–(36), we can estimate lower bounds on time-dependent effects. (For the NIF system, these equations provide only lower limits since they neglect the heat capacity of the H–He gas fill and other materials inside the hohlraum.) Assuming the baseline NIF laser pulse shape [29,34,52] and $P_N\propto P_{\rm Laser}$, we can approximate P_N as being proportional to t^4 for $\sim$3 ns before it peaks. Using Rosen's albedo model [1,20,30,36,52,69,85] and Eqs. (16), (17), and (36), we find that during this time $\tau_{\rm HN}\sim 0.07$ ns, and $\delta\sim 9\%$ at $t=3$ ns. Assuming that afterward P_N is constant for 2 ns at peak power, we find [using Eqs. (12), (13), and (36)] that over most of this interval $\tau_{\rm HN}\sim 0.085$ ns and δ is negligible.

One of the standard z-pinch-driven hohlraums fielded on the Z accelerator [54,62,74,81,104] has a centrally located z pinch and can be modeled as described in Secs. V and VI. For this system $A_S\approx 6\times 10^{-5}\,{\rm m}^2$, $A_W=1.50\times 10^{-3}\,{\rm m}^2$, $A_H=5.65\times 10^{-5}\,{\rm m}^2$, and $V=4.5\times 10^{-6}\,{\rm m}^3$. Because of gap closure we estimate from experiments conducted on Z that $A_G\approx 6.9\times 10^{-5}\,{\rm m}^2$, 50% of its initial value. Assuming T_W

peaks for 3 ns at 132 eV (as discussed below) and Rosen's albedo model [1,20,30,36,52,69,85], we obtain that at peak temperature $\alpha_W = 0.85$. According to calculations by Vesey and co-workers [61,71,81], $\alpha_G \approx 0.34$; hence $g = 0.87$.

To estimate P_S we use measurements of P_{SL} made on shots taken with nine large diagnostic apertures in the hohlraum wall. For this system the average value of P_{SL} is approximately 122 TW and $g_L = 0.97$. Consequently, from Eq. (48) we have $P_S = (g_L/g) P_{\mathrm{SL}} = 136\,\mathrm{TW}$. Using this value and Eq. (41), we estimate that in the standard hohlraum system (without the large apertures) T_R peaks at 137 eV, and [from Eq. (5)] the wall temperature $T_W = (\alpha_W)^{1/4} T_R = 132\,\mathrm{eV}$. The measured value of T_W is 133 ± 7 eV [115].

From Eq. (44) we estimate that during the 5-ns rise of the x-ray power pulse $\tau_H \sim 0.12\,\mathrm{ns}$. Assuming $P_S \propto t^4$ (the source temperature is approximately proportional to t) during this time, we use Eqs. (14)–(17) (expressed in terms of P_S and τ_H) to find $\delta \approx 100\%$ at $t = 0$, and 10% at $t = 5$ ns. Assuming $n = 1$, $N = 1.9 \times 10^{19}$, and $\gamma = 4.9 \times 10^{14}$ K/s, we obtain from Eq. (55) that $\tau_S = 3$ ns; hence from Eq. (56) we estimate that $\varepsilon = 10\%$ at $t = 0$ and is negligible at 5 ns. Assuming that afterward P_S and T_{SL} are to a good approximation constant for 3 ns at peak power, we estimate with Eqs. (12) and (13) (expressed in terms of P_S and τ_H) and Eq. (56) that during most of this interval δ and ε can be neglected.

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[1] M. D. Rosen (unpublished).
[2] P. Herrmann, R. Pakula, I. B. Földes, R. Sigel, G. D. Tsakiris, and S. Witkowski, Z. Naturforsch. Teil A **41A**, 767 (1986).
[3] R. Pakula and R. Sigel, Z. Naturforsch. Teil A **41A**, 463 (1986).
[4] T. Mochizuki, T. Yabe, H. Azechi, K. Tanaka, T. Boehly, N. Miyanaga, H. Nishimura, S. Ido, M. Yamanaka, K. Nishihara, T. Norimatsu, T. Jitsuno, M. Nakatsuka, K. Mima, S. Nakai, C. Yamanaka, R. Sigel, G. D. Tsakiris, K. Eidmann, P. Herrmann, R. Pakula, P. Sachsenmaier, S. Sakabe, and S. Witkowski, Nucl. Fusion Suppl. **3**, 25 (1987).
[5] S. Sakabe, R. Sigel, G. D. Tsakiris, I. B. Földes, and P. Herrmann, Phys. Rev. A **38**, 5756 (1988).
[6] R. Sigel, R. Pakula, S. Sakabe, and G. D. Tsakiris, Phys. Rev. A **38**, 5779 (1988).
[7] G. D. Tsakiris and R. Sigel Phys. Rev. A **38**, 5769 (1988).
[8] K. Kondo, H. Nishimura, H. Sakurai, K. Nishihara, Y. Izawa, Y. Kato, C. Yamanaka, and S. Nakai, Jpn. J. Appl. Phys., Part 1 **28**, 1695 (1989).
[9] G. M. Wing and J. D. Zahrt, Transp. Theory Stat. Phys. **18**, 447 (1989–1990).
[10] R. Sigel, G. D. Tsakiris, F. Lavarenne, J. Massen, R. Fedosejevs, J. Meyer-ter-Vehn, M. Murakami, K. Eidmann, S. Witkowski, H. Nishimura, Y. Kato, H. Takabe, T. Endo, K. Kondo, H. Shiraga, S. Sakabe, T. Jitsuno, M. Takagi, C. Yamanaka, and S. Nakai, Phys. Rev. Lett. **65**, 587 (1990).
[11] G. D. Tsakiris, J. Massen, R. Sigel, F. Lavarenne, R. Fedosejevs, J. Meyer-ter-Vehn, K. Eidmann, S. Witkowski, H. Nishimura, Y. Kato, H. Takabe, T. Endo, K. Kondo, H. Shiraga, S. Sakabe, T. Jitsuno, M. Takagi, C. Yamanaka, and S. Nakai, Phys. Rev. A **42**, 6188 (1990).
[12] E. M. Campbell, Laser Part. Beams **9**, 209 (1991).
[13] K. Kondo, H. Nishimura, Y. Kato, and S. Nakai, Jpn. J. Appl. Phys., Part 1 **30**, 839 (1991).
[14] M. Murakami and J. Meyer-ter-Vehn, Nucl. Fusion **31**, 1315 (1991).
[15] H. Nishimura, Y. Kato, H. Takabe, T. Endo, K. Kondo, H. Shiraga, S. Sakabe, T. Jitsuno, M. Takagi, C. Yamanaka, S. Nakai, R. Sigel, G. D. Tsakiris, J. Massen, M. Murakami, F. Lavarenne, R. Fedosejevs, J. Meyer-ter-Vehn, K. Eidmann, and S. Witkowski, Phys. Rev. A **44**, 8323 (1991).
[16] V. P. Smirnov, Plasma Phys. Controlled Fusion **33**, 1697 (1991).
[17] R. Sigel, G. D. Tsakiris, F. Lavarenne, J. Massen, R. Fedosejevs, K. Eidmann, J. Meyer-ter-Vehn, M. Murakami, S. Witkowski, H. Nishimura, Y. Kato, H. Takabe, T. Endo, K. Kondo, H. Shiraga, S. Sakabe, T. Jitsuno, M. Takagi, S. Nakai, and C. Yamanaka, Phys. Rev. A **45**, 3987 (1992).
[18] R. Cauble, D. W. Phillion, T. J. Hoover, N. C. Holmes, J. D. Kilkenny, and R. W. Lee, Phys. Rev. Lett. **70**, 2102 (1993).
[19] J. Massen, G. D. Tsakiris, and R. Sigel, Phys. Rev. E **48**, 2073 (1993).
[20] M. D. Rosen, Lawrence Livermore National Laboratory Report No. UCRL-ID-119916, 1993 (unpublished).
[21] R. Sigel, H. Baumhacker, G. Brederlow, K. Eidmann, E. Fill, J. Massen, J. Meyer-ter-Vehn, W. Schwanda, Ch. Stöckl, G. D. Tsakiris, R. Volk, S. Witkowski, and K. J. Witte, Laser Part. Beams **11**, 167 (1993).
[22] M. D. Cable, S. P. Hatchett, J. A. Caird, J. D. Kilkenny, H. N. Kornblum, S. M. Lane, C. Laumann, R. A. Lerche, T. J. Murphy, J. Murray, M. B. Nelson, D. W. Phillion, H.

Powell, and D. B. Ress, Phys. Rev. Lett. **73**, 2316 (1994).

[23] T. R. Dittrich, B. A. Hammel, C. J. Keane, R. McEachern, R. E. Turner, S. W. Haan, and L. J. Suter, Phys. Rev. Lett. **73**, 2324 (1994).

[24] D. D.-M. Ho, J. D. Lindl, and M. Tabak Nucl. Fusion **34**, 1081 (1994).

[25] R. L. Kauffman, L. J. Suter, C. B. Darrow, J. D. Kilkenny, H. N. Kornblum, D. S. Montgomery, D. W. Phillion, M. D. Rosen, A. R. Thiessen, R. J. Wallace, and F. Ze, Phys. Rev. Lett. **73**, 2320 (1994).

[26] Th. Löwer, R. Sigel, K. Eidmann, I. B. Földes, S. Hüller, J. Massen, G. D. Tsakiris, S. Witkowski, W. Preuss, H. Nishimura, H. Shiraga, Y. Kato, S. Nakai, and T. Endo, Phys. Rev. Lett. **72**, 3186 (1994).

[27] J. Massen, G. D. Tsakiris, K. Eidmann, I. B. Földes, Th. Löwer, R. Sigel, S. Witkowski, H. Nishimura, T. Endo, H. Shiraga, M. Takagi, Y. Kato, and S. Nakai, Phys. Rev. E **50**, 5130 (1994).

[28] L. J. Suter, A. A. Hauer, L. V. Powers, D. B. Ress, N. Delameter, W. W. Hsing, O. L. Landen, A. R. Thiessen, and R. E. Turner, Phys. Rev. Lett. **73**, 2328 (1994).

[29] S. W. Haan, S. M. Pollaine, J. D. Lindl, L. J. Suter, R. L. Berger, L. V. Powers, W. E. Alley, P. A. Amendt, J. A. Futterman, W. K. Levedahl, M. D. Rosen, D. P. Rowley, R. A. Sacks, A. I. Shestakov, G. L. Strobel, M. Tabak, S. V. Weber, G. B. Zimmerman, W. J. Krauser, D. C. Wilson, S. V. Coggeshall, D. B. Harris, N. M. Hoffman, and B. H. Wilde, Phys. Plasmas **2**, 2480 (1995).

[30] M. D. Rosen, Lawrence Livermore National Laboratory Report No. UCRL-JC-121585, 1995 (unpublished).

[31] K. S. Budil, B. A. Remington, T. A. Peyser, K. O. Mikaelian, P. L. Miller, N. C. Woolsey, W. M. Wood-Vasey, and A. M. Rubenchik, Phys. Rev. Lett. **76**, 4536 (1996).

[32] M. S. Derzon, G. A. Chandler, R. J. Dukart, D. J. Johnson, R. J. Leeper, M. K. Matzen, E. J. McGuire, T. A. Mehlhorn, A. R. Moats, R. E. Olson, and C. L. Ruiz, Phys. Rev. Lett. **76**, 435 (1996).

[33] K. H. Kang, N. A. Tahir, and J. A. Maruhn, Plasma Phys. Controlled Fusion **38**, 165 (1996).

[34] W. J. Krauser, N. M. Hoffman, D. C. Wilson, B. H. Wilde, W. S. Varnum, D. B. Harris, F. J. Swenson, P. A. Bradley, S. W. Haan, S. M. Pollaine, A. S. Wan, J. C. Moreno, and P. A. Amendt, Phys. Plasmas **3**, 2084 (1996).

[35] T. J. Orzechowski, M. D. Rosen, H. N. Kornblum, J. L. Porter, L. J. Suter, A. R. Thiessen, and R. J. Wallace, Phys. Rev. Lett. **77**, 3545 (1996).

[36] M. D. Rosen, Phys. Plasmas **3**, 1803 (1996), and references therein.

[37] L. J. Suter, R. L. Kauffman, C. B. Darrow, A. A. Hauer, H. Kornblum, O. L. Landen, T. J. Orzechowski, D. W. Phillion, J. L. Porter, L. V. Powers, A. Richard, M. D. Rosen, A. R. Thiessen, and R. Wallace, Phys. Plasmas **3**, 2057 (1996).

[38] J. P. Apruzese, R. W. Clark, J. Davis, and P. C. Kepple, Phys. Rev. Lett. **79**, 3190 (1997).

[39] C. Decker, R. E. Turner, O. L. Landen, L. J. Suter, P. Amendt, H. N. Kornblum, B. A. Hammel, T. J. Murphy, J. Wallace, N. D. Delamater, P. Gobby, A. A. Hauer, G. R. Magelssen, J. A. Oertel, J. Knauer, F. J. Marshall, D. Bradley, W. Seka, and J. M. Soures, Phys. Rev. Lett. **79**, 1491 (1997).

[40] M. S. Derzon, T. J. Nash, G. O. Allshouse, A. J. Antolak, C. Deeney, M. Hurst, J. S. McGurn, D. J. Muron, J. F. Seamen, J. MacFarlane, T. Demiris, L. Hrubesh, H. Lewis, D. Ryutov, T. Barber, T. Gilliland, D. Jobe, and S. Lazier, Rev. Sci. Instrum. **68**, 848 (1997).

[41] T. R. Dittrich, S. W. Haan, S. Pollaine, A. K. Burnham, and G. L. Strobel, Fusion Technol. **31**, 402 (1997).

[42] M. K. Matzen, Phys. Plasmas **4**, 1519 (1997).

[43] J. Meyer-ter-Vehn, Plasma Phys. Controlled Fusion **39**, B39 (1997).

[44] R. E. Olson, J. L. Porter, G. A. Chandler, D. L. Fehl, D. O. Jobe, R. J. Leeper, M. K. Matzen, J. S. McGurn, D. D. Noack, L. E. Ruggles, P. Sawyer, J. A. Torres, M. Vargas, D. M. Zagar, H. N. Kornblum, T. J. Orzechowski, D. W. Phillion, L. J. Suter, A. R. Thiessen, and R. J. Wallace, Phys. Plasmas **4**, 1818 (1997).

[45] F. Ze, S. H. Langer, R. L. Kauffman, J. D. Kilkenny, O. Landen, D. Ress, M. D. Rosen, L. J. Suter, R. J. Wallace, and J. D. Wiedwald, Phys. Plasmas **4**, 778 (1997).

[46] J. H. Brownell, R. L. Bowers, K. D. McLenithan, and D. L. Peterson, Phys. Plasmas **5**, 2071 (1998).

[47] D. Colombant, M. Klapsich, and A. Bar-Shalom, Phys. Rev. E **57**, 3411 (1998).

[48] T. R. Dittrich, S. W. Haan, M. M. Marinak, S. M. Pollaine, and R. McEachern, Phys. Plasmas **5**, 3708 (1998).

[49] S. H. Glenzer, L. J. Suter, R. E. Turner, B. J. MacGowan, K. G. Estabrook, M. A. Blain, S. N. Dixit, B. A. Hammel, R. L. Kauffman, R. K. Kirkwood, O. L. Landen, M.-C. Monteil, J. D. Moody, T. J. Orzechowski, D. M. Pennington, G. F. Stone, and T. L. Weiland, Phys. Rev. Lett. **80**, 2845 (1998).

[50] D. D.-M. Ho, J. A. Harte, and M. Tabak, Nucl. Fusion **38**, 701 (1998).

[51] H. Hora, H. Azechi, Y. Kitagawa, K. Mima, M. Murakami, S. Nakai, K. Nishihara, H. Takabe, C. Yamanaka, M. Yamanaka, and T. Yamanaka, J. Plasma Phys. **60**, 743 (1998).

[52] J. D. Lindl, *Inertial Confinement Fusion* (Springer-Verlag, New York, 1998).

[53] T. J. Murphy, J. M. Wallace, N. D. Delamater, Cris W. Barnes, P. Gobby, A. A. Hauer, E. L. Lindman, G. Magelssen, J. B. Moore, J. A. Oertel, R. Watt, O. L. Landen, P. Amendt, M. Cable, C. Decker, B. A. Hammel, J. A. Koch, L. J. Suter, R. E. Turner, R. J. Wallace, F. J. Marshall, D. Bradley, R. S. Craxton, R. Keck, J. P. Knauer, R. Kremens, and J. D. Schnittman, Phys. Plasmas **5**, 1960 (1998).

[54] J. L. Porter, Bull. Am. Phys. Soc. **42**, 1948 (1998).

[55] R. Ramis, J. Ramírez, J. J. Honrubia, J. Meyer-ter-Vehn, A. R. Piriz, J. Sanz, L. F. Ibáñez, M. M. Sánchez, and M. de laTorre, Nucl. Instrum. Methods Phys. Res. A **415**, 93 (1998).

[56] G. N. Remizov, Yu. A. Romanov, N. A. Ryabikina, R. M. Shagaliev, L. L. Vakhlamova, V. V. Vatulin, O. A. Vinokurov, R. Bock, K.-H. Kang, and J. A. Maruhn, Nucl. Instrum. Methods Phys. Res. A **415**, 139 (1998).

[57] M. Tabak, D. Callahan-Miller, D. D.-M. Ho, and G. B. Zimmerman, Nucl. Fusion **38**, 509 (1998).

[58] M. Tabak and D. A. Callahan-Miller, Phys. Plasmas **5**, 1895 (1998).

[59] M. Tabak and D. Callahan-Miller, Nucl. Instrum. Methods Phys. Res. A **415**, 75 (1998).

[60] G. Velarde, J. M. Perlado, E. Alonso, M. D. Cobo, A. Crisol, L. Doreste, J. M. Gil, L. Gonzalez, J. Honrubia, L. F. Ibanez, P. Martel, E. Minguez, J. M. Martinez-Val, F. Ogando, M. Piera, R. Piriz, J. Ramirez, R. Ramis, J. G. Rubiano, M. Sanchez, J. Sanz, G. J. Sanz, and P. Velarde, Nucl. Instrum. Methods Phys. Res. A **415**, 35 (1998).

[61] R. A. Vesey and T. A. Mehlhorn, Bull. Am. Phys. Soc. **43**, 1903 (1998).

[62] K. L. Baker, J. L. Porter, L. E. Ruggles, G. A. Chandler, C. Deeney, M. Vargas, A. Moats, K. Struve, J. Torres, J. McGurn, W. W. Simpson, D. L. Fehl, R. E. Chrien, W. Matuska, and G. C. Idzorek, Appl. Phys. Lett. **75**, 775 (1999).

[63] J. H. Hammer, M. Tabak, S. C. Wilks, J. D. Lindl, D. S. Bailey, P. W. Rambo, A. Toor, G. B. Zimmerman, and J. L. Porter, Jr., Phys. Plasmas **6**, 2129 (1999).

[64] J. D. Kilkenny, T. P. Bernat, B. A. Hammel, R. L. Kauffman, O. L. Landen, J. D. Lindl, B. J. MacGowan, J. A. Paisner, and H. T. Powell, Laser Part. Beams **17**, 159 (1999).

[65] R. J. Leeper *et al.*, Nucl. Fusion **39**, 1283 (1999).

[66] T. J. Nash, M. S. Derzon, G. A. Chandler, R. Leeper, D. Fehl, J. Lash, C. Ruiz, G. Cooper, J. F. Seamen, J. McGurn, S. Lazier, J. Torres, D. Jobe, T. Gilliland, M. Hurst, R. Mock, P. Ryan, D. Nielsen, J. Armijo, J. McKenney, R. Hawn, D. Hebron, J. J. MacFarlane, D. Peterson, R. Bowers, W. Matuska, and D. D. Ryotov, Phys. Plasmas **6**, 2023 (1999).

[67] R. E. Olson, G. A. Chandler, M. S. Derzon, D. E. Hebron, J. S. Lash, R. J. Leeper, T. J. Nash, G. E. Rochau, T. W. L. Sanford, N. B. Alexander, and C. R. Gibson, Fusion Technol. **35**, 260 (1999).

[68] W. Pei, T. Chang, G. Wang, X. Zhang, C. Sui, and J. Zhang, Phys. Plasmas **6**, 3337 (1999).

[69] M. D. Rosen, Phys. Plasmas **6**, 1690 (1999).

[70] T. W. L. Sanford, R. E. Olson, R. L. Bowers, G. A. Chandler, M. S. Derzon, D. E. Hebron, R. J. Leeper, R. C. Mock, T. J. Nash, D. L. Peterson, L. E. Ruggles, W. W. Simpson, K. W. Struve, and R. A. Vesey, Phys. Rev. Lett. **83**, 5511 (1999).

[71] R. A. Vesey, M. Cuneo, D. Hanson, J. Porter, T. Mehlhorn, L. Ruggles, W. Simpson, M. Vargas, J. Hammer, and O. Landen, Bull. Am. Phys. Soc. **44** (7), 227 (1999).

[72] J. M. Wallace, T. J. Murphy, N. D. Delamater, K. A. Klare, J. A. Oertel, G. R. Magelssen, E. L. Lindman, A. A. Hauer, P. L. Gobby, J. D. Schnittman, R. S. Craxton, W. Seka, R. Kremens, D. Bradley, S. M. Pollaine, R. E. Turner, O. L. Landen, D. Drake, and J. J. MacFarlane, Phys. Rev. Lett. **82**, 3807 (1999).

[73] K. Witte, M. Basko, H. Baumhacker, A. Böswald, K. Eidmann, R. Fedosejevs, E. Fill, V. Kondrashov, A. Kendl, T. Löwer, Y. Li, P. X. Lu, J. Meyer-ter-Vehn, G. Pretzler, A. Saemann, R. Sigel, G. Tsakiris, X. Wang, A. Benuzzi, B. Faral, C. Chenais-Popovics, M. Koenig, H. Merdji, D. Batani, D. Beretta, C. Danson, and T. Hall, Fusion Eng. Des. **44**, 147 (1999).

[74] K. L. Baker, J. L. Porter, L. E. Ruggles, G. A. Chandler, C. Deeney, M. Vargas, A. Moats, K. Struve, J. Torres, J. S. McGurn, W. W. Simpson, D. L. Fehl, D. O. Jobe, R. E. Chrien, W. Matuska, and G. C. Idzorek, Phys. Plasmas **7**, 681 (2000).

[75] G. R. Bennett, J. M. Wallace, T. J. Murphy, R. E. Chrien, N. D. Delamater, P. L. Gobby, A. A. Hauer, K. A. Klare, J. A. Oertel, R. G. Watt, D. C. Wilson, W. S. Varnum, R. S. Craxton, V. Yu. Glebov, J. D. Schnittman, C. Stoeckl, S. M. Pollaine, and R. E. Turner, Phys. Plasmas **7**, 2594 (2000).

[76] D. Callahan-Miller and M. Tabak, Phys. Plasmas **7**, 2083 (2000).

[77] R. Olson, G. Chandler, and R. Leeper, Bull. Am. Phys. Soc. **45** (7), 298 (2000).

[78] T. W. L. Sanford, R. E. Olson, R. A. Vesey, G. A. Chandler, D. E. Hebron, R. C. Mock, R. J. Leeper, T. J. Nash, C. L. Ruiz, L. E. Ruggles, W. W. Simpson, R. L. Bowers, W. Matuska, D. L. Peterson, and R. R. Peterson, Fusion Technol. **38**, 11 (2000).

[79] T. W. L. Sanford, R. E. Olson, R. C. Mock, G. A. Chandler, R. J. Leeper, T. J. Nash, L. E. Ruggles, W. W. Simpson, K. W. Struve, D. L. Peterson, R. L. Bowers, and W. Matuska, Phys. Plasmas **7**, 4669 (2000).

[80] L. Suter, J. Rothenberg, D. Munro, B. Van Wonterghem, and S. Haan, Phys. Plasmas **7**, 2092 (2000).

[81] M. E. Cuneo, R. A. Vesey, J. H. Hammer, and J. L. Porter Jr., Laser and Part. Beams (to be published).

[82] M. E. Cuneo, R. A. Vesey, J. L. Porter, Jr., G. A. Chandler, D. L. Fehl, T. L. Gilliland, D. L. Hanson, J. S. McGurn, P. G. Reynolds, L. E. Ruggles, J. J. Seamen, R. B. Spielman, K. W. Struve, W. A. Stygar, W. W. Simpson, J. A. Torres, D. F. Wenger, J. H. Hammer, P. W. Rambo, D. L. Peterson, and G. C. Idzorek, Phys. Plasmas **8**, 2257 (2001).

[83] S. A. Slutz, M. R. Douglas, J. S. Lash, R. A. Vesey, G. A. Chandler, T. J. Nash, and M. S. Derzon, Phys. Plasmas **8**, 1673 (2001).

[84] R. E. Olson, T. W. L. Sanford, G. A. Chandler, R. J. Leeper, R. C. Mock, J. S. McGurn, S. E. Lazier, J. C. Armijo, S. Dropinski, R. E. Ruggles, W. W. Simpson, J. A. Torres, and C. Wakefield, Rev. Sci. Instrum. **72**, 1214 (2001).

[85] R. E. Marshak, Phys. Fluids **1**, 24 (1958).

[86] R. Pakula and R. Sigel, Phys. Fluids **28**, 232 (1985); **29**, 1340(E) (1986).

[87] F. Reif, *Fundamentals of Statistical and Thermal Physics* (McGraw-Hill, New York, 1965), p. 387.

[88] R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles* (Wiley, New York, 1974), p. 26.

[89] J. F. Cuderman and K. M. Gilbert, Rev. Sci. Instrum. **46**, 53 (1975).

[90] H. N. Kornblum, R. L. Kauffman, and J. A. Smith, Rev. Sci. Instrum. **57**, 2179 (1986).

[91] D. R. Kania, L. S. Pan, P. Bell, O. L. Landen, H. Kornblum, P. Pianetta, and M. D. Perry, J. Appl. Phys. **68**, 124 (1990).

[92] D. R. Kania, L. Pan, H. Kornblum, P. Bell, O. N. Landen, and P. Pianetta, Rev. Sci. Instrum. **61**, 2765 (1990).

[93] L. S. Pan, D. R. Kania, P. Pianetta, and O. L. Landen, Appl. Phys. Lett. **57**, 623 (1990).

[94] R. B. Spielman, Rev. Sci. Instrum. **63**, 5056 (1992).

[95] F. Ze, R. L. Kauffman, J. D. Kilkenny, J. Wielwald, P. M. Bell, R. Hanks, J. Stewart, D. Dean, J. Bower, and R.

Wallace, Rev. Sci. Instrum. **63**, 5124 (1992).
[96] A. Hauer, N. Delamater, D. Ress, W. Hsing, L. Suter, L. Powers, O. Landen, D. Harris, R. Thiessen, G. Magelssen, E. Lindman, D. Phillion, P. Amendt, R. Watt, and B. Hammel, Rev. Sci. Instrum. **66**, 672 (1995).
[97] R. L. Kauffman, H. N. Kornblum, D. W. Phillion, C. B. Darrrow, B. F. Lasinski, L. J. Suter, A. R. Theissen, R. J. Wallace, and F. Ze, Rev. Sci. Instrum. **66**, 678 (1995).
[98] R. B. Spielman, Rev. Sci. Instrum. **66**, 867 (1995).
[99] D. L. Fehl and F. Biggs, Rev. Sci. Instrum. **68**, 890 (1997).
[100] D. L. Fehl, G. A. Chandler, F. Biggs, R. J. Dukart, A. R. Moats, and R. J. Leeper, Rev. Sci. Instrum. **68**, 843 (1997).
[101] S. Han, Rev. Sci. Instrum. **68**, 647 (1997).
[102] G. C. Idzorek and R. J. Bartlett, Proc. SPIE **3114**, 349 (1997).
[103] R. B. Spielman, L. E. Ruggles, R. E. Pepping, S. P. Breeze, J. S. McGurn, and K. W. Struve, Rev. Sci. Instrum. **68**, 782 (1997).
[104] K. L. Baker, J. L. Porter, L. E. Ruggles, D. L. Fehl, G. A. Chandler, M. Vargas, L. P. Mix, W. W. Simpson, C. Deeney, R. E. Chrien, and G. C. Idzorek, Rev. Sci. Instrum. **70**, 2012 (1999).
[105] G. A. Chandler, C. Deeney, M. Cuneo, D. L. Fehl, J. S. McGurn, R. B. Spielman, J. A. Torres, J. L. McKenney, J. Mills, and K. W. Struve, Rev. Sci. Instrum. **70**, 561 (1999).
[106] R. B. Spielman, C. Deeney, D. L. Fehl, D. L. Hanson, N. R. Keltner, J. S. McGurn, and J. L. McKenney, Rev. Sci. Instrum. **70**, 651 (1999).
[107] R. E. Turner, O. L. Landen, P. Bell, R. Costa, and D. Hargrove, Rev. Sci. Instrum. **70**, 656 (1999).
[108] D. L. Fehl, F. Biggs, G. A. Chandler, and W. A. Stygar, Rev. Sci. Instrum. **71**, 3072 (2000).
[109] R. Byron Bird, Warren E. Stewart, and Edwin N. Lightfoot, *Transport Phenomena* (Wiley, New York, 1960), pp. 437–443.
[110] Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Academic, New York, 1966), Vol. I.
[111] Y. T. Lee, J. Quant. Spectrosc. Radiat. Transf. **38**, 131 (1987).
[112] *CRC Handbook of Chemistry and Physics*, 81st ed., edited by David R. Lide (CRC, New York, 2000), pp. 10–175 to 10–177.
[113] T. A. Carlson, C. W. Nestor, Jr., N. Wasserman, and J. D. McDowell, At. Data **2**, 63 (1970).
[114] S. L. Thompson and H. S. Lauson, Sandia National Laboratories Report No. SC-RR-71-0713, 1972.
[115] M. E. Cuneo (private communication).