Analytic models of high-temperature hohlraums

W. A. Stygar, R. E. Olson, R. B. Spielman, and R. J. Leeper

Sandia National Laboratories, MS 1194, Albuquerque, New Mexico 87185-1194

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Abstract

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, $P_N = \{(1 - \alpha_w)A_w + A_H + [(1 - \alpha_c)(A_S + A_w\alpha_w)A_c/A_T]\}\sigma T_{RC}^4$ 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 (NIF) hohlraum is 15% higher than predicted by previous analytic expressions. A model of a hohlraum that encloses a z pinch is also presented.

I. INTRODUCTION

High-temperature hohlraums are being used for indirect-drive inertial-confinement-fusion (ICF), high-energy-density, equation-of-state, and astrophysics research [1-82]. Laser-driven-hohlraum experiments have been conducted at 100-300 eV [2,4,5-12,14-22,24-26,38,43,48,51,52,71,74,77]. 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 [28,33,35,40,50,51,63,80]. Temperatures of 60-180 eV have been produced in z-pinch-driven cavities

[15,41,43,45,53,61,64,65,69,73,76,78,79,81]. A 60-MA z-pinch driver would achieve 210-300 eV [62,64,66]. Megajoule heavy-ion beams focused to spots a few millimeters in diameter would drive hohlraums to 200-300 eV [13,23,32,49,51,54-58,75].

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 [1,6,8-10,12-14,19,24,29,35,36,51,62,67,76].

In Section 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 temperatures. For a laser-driven hohlraum the model leads to a definition of laser-conversion efficiency in terms of the net source power. In Section 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. [83].) 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 coworkers [38]. In Section IV, following ideas developed by Murakami and Meyer-ter-Vehn [13], 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 Section 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 Tsarkis et. al. [10], Rosen [19,35], Hammer et. al. [62], and Cuneo et. al. [76].

The models outlined in Sections 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 [1,29,35,51,84] and Pakula, Sigel et. al [3,6,9,14,18,84,85]. 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 in a partially-open geometry, as described in Section VI. In Section VII we comment briefly on NIF and Z-accelerator hohlraum designs.

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II. SIMPLE HOHLRAUM

We first consider 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 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 the radiation flux incident on A_T is equal to $(cU_R/4V)$, independent of the spectrum, where c is the speed of light [86]. Hence the radiation brightness temperature T_R is given by

$$\sigma T_R^4 = \frac{cU_R}{4V} \quad (1)$$

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

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

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 .) Eq. 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

$$\sigma T_s^4 = \frac{P_s}{A_s} \quad \text{and} \quad \sigma T_w^4 = \frac{P_w}{A_w} \quad (3)$$

Eqs. 1-3 can be re-written as:

$$P_s = [A_s + (1 - \alpha_w)A_w + A_H] \sigma T_R^4 + \frac{4V\sigma}{c} \frac{dT_R^4}{dt} \quad (4)$$

where α_w , the wall albedo, is defined by:

$$\alpha_w \equiv \frac{P_w}{A_w \sigma T_R^4} = \left(\frac{T_w}{T_R} \right)^4 \quad (5)$$

P_w is the sum of the incident hohlraum-radiation power reflected from the area A_w and the power reemitted. For most experiments of interest, little of the radiation incident on A_w is reflected. In this limit the albedo is due only to reemission, and might more correctly be referred to as the reemission coefficient [6].

Over time periods when $[A_s + (1 - \alpha_w)A_w + A_H]$ does not change significantly, 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 :

$$\tau_H \equiv \frac{4V}{c[A_s + (1 - \alpha_w)A_w + A_H]} \quad (6)$$

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

Eq. 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. Eq. 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

$$P_N = P_S - A_S\sigma T_R^4 \quad (7)$$

Combining Eqs. 4 and 7 gives:

$$P_N = [(1-\alpha_w)A_w + A_H]\sigma T_R^4 + \frac{4V\sigma}{c} \frac{dT_R^4}{dt} \quad (8)$$

The characteristic time required to change T_R^4 in response to a change in P_N is:

$$\tau_{HN} \equiv \frac{4V}{c[(1-\alpha_w)A_w + A_H]} \quad (9)$$

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

$$P_S - A_S\sigma T_R^4 = P_N = [(1-\alpha_w)A_w + A_H]\sigma T_R^4 \quad (10)$$

This relation 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 $[(1-\alpha_w)A_w + A_H] \rightarrow 0$, i.e., as the hohlraum becomes increasingly efficient, $T_R \rightarrow T_S$, the brightness temperature of the source.

Eq. 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 $A_S = 0$. 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 $\eta_{CE}P_{LASER}$, where η_{CE} is the instantaneous conversion efficiency from laser to x-ray power. We propose η_{CE} be defined as

$$\eta_{CE} \equiv \frac{P_N}{P_{LASER}} = \frac{P_S - A_S \sigma T_R^4}{P_{LASER}} \quad (11)$$

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 $\eta_{CE} = P_N/P_{LASER} = P_S/P_{LASER}$.

Since Eq. 10 is more convenient than Eq. 4, 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. 4, to T_R^4 as determined by Eq. 10, where δ is the fractional error. When P_S and $[A_S + (1-\alpha_w)A_w + A_H]$ are constant we estimate from Eq. 4:

$$T_R^4 = \frac{P_S}{\sigma[A_S + (1-\alpha_w)A_w + A_H]} \left[1 - \exp\left(-\frac{t}{\tau_H}\right) \right] \quad (12)$$

assuming $T_R^4 = 0$ at $t = 0$. From Eqs. 10 and 12 we obtain:

$$\delta = \exp\left(-\frac{t}{\tau_H}\right) \quad (13)$$

which equals 5% when $t \approx 3\tau_H$.

When $P_S \propto t^{4n}$ where $4n$ is a positive integer (i.e., the source temperature is approximately proportional to t^n), $[A_S + (1-\alpha_w)A_w + A_H]$ is constant, and $t \ll \tau_H$, we find from Eq. 4:

$$T_R^4 \approx \frac{P_S}{\sigma[A_S + (1-\alpha_w)A_w + A_H]} \left[\frac{t}{(4n+1)\tau_H} \right] \quad (14)$$

assuming $T_R^4 = 0$ at $t = 0$. From Eqs. 10 and 14 we obtain:

$$\delta \approx 1 - \left[\frac{t}{(4n+1)\tau_H} \right] \quad (15)$$

When $t \gg 4n\tau_H$:

$$T_R^4 \approx \frac{P_s}{\sigma[A_s + (1 - \alpha_w)A_w + A_H]} \left[1 - \left(\frac{4n}{t/\tau_H} \right) \right] \quad (16)$$

$$\delta \approx \frac{4n}{t/\tau_H} \quad (17)$$

When $P_s \propto t^4$ (and T_R is approximately proportional to t), $\delta = 5\%$ when $t \approx 80\tau_H$.

Eqs. 12-17 are expressed in terms of P_s and τ_H ; similar expressions can be readily obtained in terms of P_N and τ_{HN} .

III. T_R , α_w , AND η_{CE} IN TERMS 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} inside a hohlraum. Combining Eqs. 1 and 2 we find

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

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:

$$\sigma T_R^4 = \sigma T_T^4 = f_s \sigma T_s^4 + f_w \sigma T_w^4 \quad (19)$$

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 . Eqs. 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 [83,87-106].

Results by Decker et. al. [38] and Eq. 19 suggest that a single measurement can be used to obtain $T_R(t)$. As described in [38], 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:

$$\sigma T_R^4 = \frac{A_s + A_w}{A_T} [v_s \sigma T_s^4 + v_w \sigma T_w^4] = (f_s + f_w) \left(\frac{P_{\text{VIEW}}}{A_{\text{VIEW}}} \right) \quad (20)$$

where $P_{\text{VIEW}} \equiv A_{\text{VIEW}}(v_s \sigma T_s^4 + v_w \sigma T_w^4)$ is the total power emitted by the field of view and A_{VIEW} is its area. In such an arrangement the measured flux ($P_{\text{VIEW}}/A_{\text{VIEW}}$) 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 do not change significantly during the period of interest.

Combining Eqs. 5 and 19 gives the wall albedo:

$$\alpha_w = \frac{1}{\left(\frac{A_s}{A_T} \right) \left(\frac{T_s}{T_w} \right)^4 + \left(\frac{A_w}{A_T} \right)} = \frac{1}{f_s \left(\frac{T_s}{T_w} \right)^4 + f_w} \quad (21)$$

Hence $\alpha_w(t)$ can be obtained inside a hohlraum from time-resolved measurements of f_s , f_w , and $(T_s/T_w)^4$. These quantities might be obtained, for example, with an x-ray-framing camera [93]. It has been proposed [34,46,75,80] 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. 51:

$$\alpha_w = \frac{1}{\left(\frac{A_s}{A_w} \right) \left(\frac{T_s}{T_w} \right)^4 + \left(\frac{A_w - A_s - A_H}{A_w} \right)} \quad (22)$$

However Eqs. 21 and 22 are approximately equivalent when $A_w \approx A_T$.

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

$$\eta_{CE} = \frac{A_S}{P_{LASER}} [(1-f_S)\sigma T_S^4 - f_W\sigma T_W^4] \quad (23)$$

Consequently we can determine $\eta_{CE}(t)$ 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 [93] and a filtered array of x-ray detectors, as described in [64,83]. According to Eqs. 19, 21, and 23, such a system could in principle provide $T_R(t)$, $\alpha_E(t)$, and $\eta_{CE}(t)$ using a single aperture in the hohlraum wall. When f_S and f_W are 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 Sections 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 [13]. 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 [28,33,35,40,47,50,51,63,80], distributed-radiator heavy-ion-beam-driven hohlraums [56-58,75], and the central cavity in the z-pinch-driven system proposed by Hammer et. al [62,64,76,81].

As in Sections 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):

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

where

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

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 [13,107]:

$$\sigma T_{RC}^4 = \frac{P_S + P_W}{A_S + A_W + A_H} = \frac{P_S + \alpha_W A_W \sigma T_R^4}{A_T} \quad (26)$$

Combining Eqs. 7, 24, and 26 gives

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

and

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

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:

$$\eta_{\text{CAPSULE}} \equiv \frac{(1 - \alpha_C)A_C \sigma T_{RC}^4}{P_N} = \left[\frac{(1 - \alpha_W)A_W}{(1 - \alpha_C)A_C} + \frac{A_H}{(1 - \alpha_C)A_C} + \left(\frac{A_S + \alpha_W A_W}{A_T} \right) \right]^{-1} \quad (29)$$

As $\alpha_C \rightarrow 0$ and $A_C \rightarrow A_T$, then $\eta_{\text{CAPSULE}} \rightarrow 1$, 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. (For example, the expression for the coupling efficiency given as Eq. 7.37 in Ref. 51 is derived from Eqs. 7.30 and 7.36. Eq. 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. 13 assumes the source and holes areas are negligible. If we assume (using the notation of Ref. 13) that $P_{S1} = A_1 P_S / A_2$; 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 [32,49,54,55,64,66]. (Such shields would, of course, also prevent the sources from receiving direct radiation from the capsule.) For such a system, we make the simplifying assumptions that the area of the shields and A_S are much less than A_W , the radiation flux incident on the source is the same as the flux on the capsule, and the source and capsule are directly irradiated only by power emitted from the region defined by A_W .

We define σT_{RS}^4 to be the flux incident on A_S , σT_{RC}^4 the flux incident on A_C , and σT_R^4 the flux incident on the area $(A_W + A_H)$. Under these conditions Eq. 24 and 26 become:

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

$$\sigma T_{RC}^4 = \sigma T_{RS}^4 = \frac{P_W}{A_W + A_H} = \frac{\alpha_W A_W \sigma T_R^4}{A_W + A_H} \quad (31)$$

Combining Eqs. 30 and 31 gives:

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

The capsule coupling efficiency is:

$$\eta_{\text{CAPSULE}} \equiv \frac{(1-\alpha_C)A_C\sigma T_{\text{RC}}^4}{P_N} = \left[\left(\frac{((1-\alpha_W)A_W + A_H)(A_W + A_H)}{\alpha_W A_W (1-\alpha_C)A_C} \right) + 1 \right]^{-1}. \quad (33)$$

As $\alpha_C \rightarrow 0$ and $A_C \rightarrow A_W + A_H$, then $\eta_{\text{CAPSULE}} \rightarrow \alpha_W A_W / (A_W + A_H)$, as expected.

As noted previously, the expression for the coupling efficiency given as Eq. 3.9 in Ref. 13 assumes the source and holes areas are negligible. If we assume (using the notation of Ref. 13) that $P_{\text{SI}} = 0$; i.e., that the source is not allowed to irradiate the capsule directly, this expression becomes identical to Eq. 33 above when $A_S = A_H = 0$.

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 the source irradiates the capsule directly, then $T_{\text{RC}} = T_R$, and we can generalize the arguments in Section II to obtain:

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

Eqs. 27, 28, and 32 are consistent with Eq. 34 when $A_H \ll A_W$ and $\alpha_W \approx 1$, since in this limit the flux incident on A_T approaches the flux emitted, and $T_R \rightarrow T_{\text{RC}}$.

The hohlraum time constants become:

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

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

Other results obtained in Sections II and III follow immediately.

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

$$\eta_{\text{CAPSULE}} \equiv \frac{(1-\alpha_c)A_c\sigma T_R^4}{P_N} = \left[\frac{(1-\alpha_w)A_w}{(1-\alpha_c)A_c} + \frac{A_H}{(1-\alpha_c)A_c} + 1 \right]^{-1} \quad (37)$$

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

V. HOHLRAUM WITH A CONVEX SOURCE

A. Two radiation temperatures

The models in Sections II, III, IV.A.1, and IV.B assume 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.

This approximates a hohlraum that encloses a z pinch, as is used in some weapon-physics and ICF experiments [41,43,53,60-62,64,66,69,70,73,76,78,79,81]. We shall assume 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):

$$P_S = A_s\sigma T_{RS}^4 + [(1-\alpha_w)A_w + A_H + (1-\alpha_G)A_G]\sigma T_R^4 \quad (38)$$

where

$$\alpha_w \equiv \frac{P_w}{A_w\sigma T_R^4} \quad \alpha_G \equiv \frac{P_G}{A_G\sigma T_R^4} \quad (39)$$

α_G , the effective albedo of area A_G , is not zero because radiation scatters from the walls of the transmission line back into the hohlraum [60,70,76]. P_G is the total power that

scatters into 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 $(A_W + A_H + A_G)$ [13,107]:

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

Combining Eqs. 38 and 40 gives

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

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

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

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 $T_{RS} = T_R$, we can generalize the arguments in Section II to obtain a single-radiation-temperature model of a hohlraum containing a z pinch:

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

Eqs. 41 and 42 are consistent with Eq. 43 when $A_H, A_G \ll A_W$ and $\alpha_W \approx 1$, since in this limit the flux incident on $(A_W + A_H + A_G)$ approaches the flux emitted by this area, and $T_R \rightarrow T_{RS}$.

The hohlraum time constants become:

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

$$\tau_{\text{HN}} \equiv \frac{4V}{c[(1-\alpha_w)A_w + A_h + (1-\alpha_g)A_g]} \quad (45)$$

Other results obtained in Sections II and III 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:

$$\frac{dU_s}{dt} = P_{\text{EXT}} + A_s \sigma T_{\text{RS}}^4 - P_s = P_{\text{EXT}} - P_N \quad (46)$$

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

$$\frac{dU_{\text{SL}}}{dt} = P_{\text{EXT}} + A_s \sigma T_{\text{RSL}}^4 - P_{\text{SL}} = P_{\text{EXT}} - P_{\text{NL}} \quad (47)$$

where the subscript "L" denotes quantities for the large-aperture system. (We assume P_{EXT} is 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:

$$gP_s = P_N = P_{\text{NL}} = g_L P_{\text{SL}} \quad (48)$$

where

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

is calculated for the hohlraum without the large diagnostic apertures, and g_L is the corresponding quantity for the large-aperture system. Eq. 48 gives the total- and net-source terms P_S and P_N as a function of P_{SL} . (We have implicitly assumed the apertures used to measure P_{SL} do not affect pinch performance.) According to Eq. 48, the total power P_S emitted by a z pinch in the hohlraum without the large apertures is greater by the factor (g_L/g) .

B. Source time constant

Eq. 48 assumes dU_R/dt , dU_S/dt , and dU_{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 $dU_S/dt = dU_{SL}/dt = 0$ 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:

$$\frac{dU_S}{dt} - \frac{dU_{SL}}{dt} = P_{NL} - P_N = g_L P_{SL} - g P_S \quad (50)$$

To develop an expression for U_S , we assume the z pinch can be modeled as a plasma with ion-charge state $Z \gg 1$, and that U_S is dominated by the kinetic energy of electrons and potential energy of ions [108]. Hence:

$$U_S = \frac{3}{2} N Z k T_S + N \sum_{j=1}^Z I_j = \frac{3}{2} N Z k T_S + N Z I_{AVE} = (0.042) N k T_S^{3/2} \equiv \beta T_S^{3/2} \quad (51)$$

where N is the number of ions, k is the Boltzmann constant, I_j is the j th ionization potential, and I_{AVE} is the average of the first Z ionization potentials. Eq. 51 sets $Z = (0.014) T_S^{1/2}$ and $I_{AVE} = 3kT_S/2$ (T_S in degrees Kelvin), which are reasonable

approximations for a high-atomic-number z-pinch at electron densities (10^{28} m^{-3}) and temperatures ($2 \times 10^6 \text{ K}$) of interest [109,110]. Similarly, $U_{SL} = \beta T_{SL}^{3/2}$. Combining these expressions for internal energy with Eq. 50 (and assuming $A_S = A_{SL}$) gives

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

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

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

When $n \geq 0$ and $t \gg [3n/(5n+2)]^{2/(5n+2)} \tau_s$:

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

where the source time constant τ_s is defined by

$$\tau_s \equiv \left[\frac{3\beta(5n+2)}{16A_S \sigma g \gamma^{5/2}} \right]^{\frac{2}{5n+2}} \quad (55)$$

As $t \rightarrow \infty$, $f \rightarrow f_s \equiv (g_L - g)/g$ where f_s is the steady-state value of f . In this limit $T_S^4 \rightarrow T_{SL}^4(1+f_s) = T_{SL}^4(g_L/g)$, and (according to Eq. 48) $P_N \rightarrow P_{NL}$.

We define $1-\epsilon$ 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:

$$\epsilon \equiv \frac{\left(\frac{g_L P_{SL}}{g} \right) - P_{SL}(1+f)}{\left(\frac{g_L P_{SL}}{g} \right)} = \left(\frac{g_L - g}{g_L} \right) \exp \left[- \left(\frac{t}{\tau_s} \right)^{\frac{5n+2}{2}} \right] \quad (56)$$

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 [28,33,35,40,50,51,63,80] can be modeled as described in Section IV.A.1. For this system $A_s = 4.0 \times 10^{-5} \text{ m}^2$, $A_w = 1.6 \times 10^{-4} \text{ m}^2$, $A_H = 1.2 \times 10^{-5} \text{ m}^2$, $A_C \sim 6 \times 10^{-6} \text{ m}^2$, $\alpha_w = 0.89$, and $\alpha_C \sim 0$ [35]. Assuming a 75% laser-conversion efficiency [35] and $P_{\text{LASER}} = 400 \text{ TW}$ [28,33,51], Eqs. 11 and 28 predict the capsule-drive temperature T_{RC} would be 303 eV. The value predicted by integrated calculations is 300 eV [28,33,51]. According to Eq. 29, $\eta_{\text{CAPSULE}} = 17\%$, which is 15% higher than predicted by previous analytic relations.

The standard z-pinch-driven hohlraum fielded on the Z accelerator [53,61,73,76,102] can be modeled as described in Sections V and VI. For this system, $A_s \approx 6 \times 10^{-5} \text{ m}^2$, $A_w = 1.50 \times 10^{-3} \text{ m}^2$, $A_H = 5.65 \times 10^{-5} \text{ m}^2$, and $V = 4.5 \times 10^{-6} \text{ m}^3$. Because of gap closure we estimate from experiments conducted on Z that $A_G \approx 6.9 \times 10^{-5} \text{ m}^2$, 50% of its initial value. Assuming T_w peaks for 3 ns at 128 eV (as discussed below) and Rosen's albedo model [1,29,35,51,84], we obtain that at peak temperature $\alpha_w = 0.85$. According to calculations by Vesey [60,70,76], $\alpha_G \approx 0.34$. Hence according to Eq. 49, $g = 0.87$.

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 110 TW [111] and $g_L = 0.97$. Consequently from Eq. 48 we have $P_s = (g_L/g)P_{\text{SL}} = 122 \text{ TW}$. Using this value and Eq. 41, we estimate that in the standard hohlraum system (without the large diagnostic apertures) T_R peaks at 133 eV, and (from Eq. 5) the wall temperature $T_w = (\alpha_w)^{1/4}T_R = 128 \text{ eV}$. The measured value of T_w is $133 \pm 7 \text{ eV}$ [111].

From Eq. 44 we estimate that during the 5-ns rise of the x-ray power pulse, $\tau_H \sim 0.1 \text{ ns}$. Assuming $P_s \propto t^4$ (the source temperature is approximately proportional to t) during this time, we use Eqs. 15 and 17 to find $\delta = 100\%$ at $t = 0$, and 8% at $t = 5 \text{ ns}$. According to Eq. 55, $\tau_s = 2.6 \text{ ns}$; hence from Eq. 56 we estimate that $\epsilon = 10\%$ 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. 13 and 56 that during most of this interval δ and ϵ are negligible.

The 4-mm-diameter 4-mm-high static-wall hohlraum fielded on the Z accelerator by Sanford et. al. [79] can be modeled as described in Section II. For this system $A_s = 1.26 \times 10^{-5} \text{ m}^2$, $A_w = 5.97 \times 10^{-5} \text{ m}^2$, $A_H = 3.14 \times 10^{-6} \text{ m}^2$, and $P_s \sim 13 \text{ TW}$. Assuming T_w peaks at 146 eV (as discussed below) for 3 ns and Rosen's albedo model [1,29,35,51,84], we estimate that at peak temperature $\alpha_w = 0.86$. Using Eqs. 5 and 10, we find T_R and T_w are expected to peak at 151 eV and 146 eV, respectively. The measured value [79] of T_w midway between the top and bottom of the hohlraum is $155 \pm 8 \text{ eV}$.

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- [1] M. D. Rosen (unpublished, 1979).
  - [2] P. Herrmann, R. Pakula, I. B. Földes, R. Sigel, G. D. Tsakiris, and S. Witkowski, *Z. Naturforsch* **41a**, 767 (1986).
  - [3] R. Pakula and R. Sigel, *Z. Naturforsch* **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, S. Witkowski, *Nuclear Fusion Supplement* **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.* **28**, 1695 (1989).
- [9] 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).
- [10] 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).
- [11] E. M. Campbell, *Laser Part. Beams* **9**, 209 (1991).
- [12] K. Kondo, H. Nishimura, Y. Kato, and S. Nakai, *Jpn. J. Appl. Phys.* **30**, 839 (1991).
- [13] M. Murakami and J. Meyer-ter-Vehn, *Nucl. Fusion* **31**, 1315 (1991).
- [14] 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).
- [15] V. P. Smirnov, *Plasma Phys. Controlled Fusion* **33**, 1697 (1991).
- [16] 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).
- [17] R. Cauble, D. W. Phillion, T. J. Hoover, N. C. Holmes, J. D. Kilkenny, and R. W. Lee, *Phys. Rev. Lett.* **70**, 2102 (1993).
- [18] J. Massen, G. D. Tsakiris, and R. Sigel, *Phys. Rev. E* **48**, 2073 (1993).
- [19] M. D. Rosen, Lawrence Livermore National Laboratory Report UCRL-ID-119916 (1993).
- [20] 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 Particle Beams* **11**, 167 (1993).
- [21] 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).
- [22] 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).
- [23] D. D.-M. Ho, J. D. Lindl, and M. Tabak, *Nucl. Fusion* **34**, 1081 (1994).

- [24] 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).
- [25] 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).
- [26] 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).
- [27] 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).
- [28] 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).
- [29] M. D. Rosen, Lawrence Livermore National Laboratory report UCRL-JC-121585 (1995).
- [30] 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).
- [31] 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).
- [32] K. H. Kang, N. A. Tahir, and J. A. Maruhn, *Plasma Phys. Contrl. Fusion* **38**, 165 (1996).
- [33] 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).
- [34] 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).
- [35] M. D. Rosen, *Phys. Plasmas* **3**, 1803 (1996), and references therein.
- [36] L. J. Suter, R. L. Kaufmann, 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).
- [37] J. P. Apruzese, R. W. Clark, J. Davis, and P. C. Kepple, *Phys. Rev. Lett.* **79**, 3190 (1997).

- [38] 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).
- [39] 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).
- [40] T. R. Dittrich, S. W. Haan, S. Pollaine, A. K. Burnham, and G. L. Strobel, *Fusion Technology* **31**, 402 (1997).
- [41] M. K. Matzen, *Phys. Plasmas* **4**, 1519 (1997).
- [42] J. Meyer-ter-Vehn, *Plasma Phys. Control. Fusion* **39**, B39 (1997).
- [43] 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).
- [44] 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).
- [45] J. Brownell, R. L. Bowers, K. D. McLenithan, and D. L. Peterson, *Phys. Plasmas* **5**, 207 (1998).
- [46] D. Colombant, M. Klapsich, and A. Bar-Shalom, *Phys. Rev. E* **57**, 3411 (1998).
- [47] T. R. Dittrich, S. W. Haan, M. M. Marinak, S. M. Pollaine, and R. McEachern, *Phys. Plasmas* **5**, 3708 (1998).
- [48] 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).
- [49] D. D.-M. Ho, J. A. Harte, and M. Tabak, *Nucl. Fusion* **38**, 701 (1998).
- [50] 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 Physics* **60**, 743 (1998).
- [51] J. D. Lindl, *Inertial Confinement Fusion* (Springer-Verlag, New York, 1998).
- [52] 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).
- [53] J. L. Porter, *Bull. Am. Phys. Soc.* **42**, 1948 (1998).

- [54] 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. Instr. and Meth. in Phys. Res. A **415**, 93 (1998).
- [55] 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. Instr. and Meth. in Phys. Res. A **415**, 139 (1998).
- [56] M. Tabak, D. Callahan-Miller, D. D.-M. Ho, and G. B. Zimmerman, Nucl. Fusion **38**, 509 (1998).
- [57] M. Tabak and D. A. Callahan-Miller, Phys. Plasmas **5**, 1895 (1998).
- [58] M. Tabak and D. Callahan-Miller, Nucl. Instr. and Meth. in Phys. Res. A **415**, 75 (1998).
- [59] 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. Instr. and Meth. in Phys. Res. A **415**, 35 (1998).
- [60] R. A. Vesey and T. A. Mehlhorn, Bull. Amer. Phys. Soc. **43**, 1903 (1998).
- [61] 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).
- [62] 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).
- [63] 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 Particle Beams **17**, 159 (1999).
- [64] R.J. Leeper et al., Nuclear Fusion, **39**,1283 (1999).
- [65] 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).
- [66] 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 Technology **35**, 260 (1999).
- [67] W. Pei, T. Chang, G. Wang, X. Zhang, C. Sui, and J. Zhang, Phys. Plasmas **6**, 3337 (1999).
- [68] M. D. Rosen, Phys. Plasmas **6**, 1690 (1999).

- [69] 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).
- [70] R. A. Vesey, M. Cuneo, D. Hanson, J. Porter, T. Mehlhorn, L. Ruggles, W. Simpson, M. Vargas, J. Hammer, and O. Landen, *Bull. Amer. Phys. Soc.* **44**, No. 7, 227 (1999).
- [71] 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).
- [72] 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 Engineering and Design* **44**, 147 (1999).
- [73] 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).
- [74] 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).
- [75] D. Callahan-Miller and M. Tabak, *Phys. Plasmas* **7**, 2083 (2000).
- [76] M. E. Cuneo, R. A. Vesey, J. H. Hammer, and J. L. Porter, Jr., to be published in *Lasers Particle Beams*.
- [77] R. Olson, G. Chandler, and R. Leeper, *Bull. Am. Phys. Soc.* **45**, No. 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 Tech.* **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, to be published in *Phys. Plasmas* **7** (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. 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., to be published in Phys. Plasmas.
- [82] S. A. Slutz, M. R. Douglas, J. S. Lash, R. A. Vesey, G. A. Chandler, T. J. Nash, and M. S. Derzon, submitted to Phys. Plasmas.
- [83] 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, to be published in Rev. Sci. Instrum. **72** (January 2001).
- [84] R. E. Marshak, Phys. Fluids **1**, 24 (1958).
- [85] R. Pakula and R. Sigel, Phys. Fluids **28**, 232 (1985); **29**, 1340(E) (1986).
- [86] F. Reif, *Fundamentals of statistical and thermal physics* (McGraw-Hill Book Company, New York, 1965) p. 387.
- [87] J. F. Cuderman and K. M. Gilbert, Rev. Sci. Instrum. **46**, 53 (1975).
- [88] H. N. Kornblum, R. L. Kaufmann, and J. A. Smith, Rev. Sci. Instrum., **57**, 2179 (1986).
- [89] 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).
- [90] D. R. Kania, L. Pan, H. Kornblum, P. Bell, O. N. Landen, and P. Pianetta, Rev. Sci. Instrum. **61**, 2765 (1990).
- [91] L. S. Pan, D. R. Kania, P. Pianetta, and O. L. Landen, Appl. Phys. Lett. **57**, 623 (1990).
- [92] R. B. Spielman, Rev. Sci. Instrum. **63**, 5056 (1992).
- [93] F. Ze, R. L. Kauffman, J. D. Kilkenny, J. Wielwald, P. M. Bell, R. Hanks, J. Stewart, D. Dean, J. Bower, R. Wallace, Rev. Sci. Instrum. **63**, 5124 (1992).
- [94] 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).
- [95] R. L. Kauffman, H. N. Kornblum, D. W. Phillion, C. B. Darrow, B. F. Lasinski, L. J. Suter, A. R. Theissen, R. J. Wallace, and F. Ze, Rev. Sci. Instrum. **66**, 678 (1995).
- [96] R. B. Spielman, Rev. Sci. Instrum. **66**, 867 (1995).
- [97] D. L. Fehl and F. Biggs, Rev. Sci. Instrum. **68**, 890 (1997).
- [98] D. L. Fehl, G. A. Chandler, F. Biggs, R. J. Dukart, A. R. Moats, and R. J. Leeper, Rev. Sci. Instrum. **68**, 843 (1997).
- [99] S. Han, Rev. Sci. Instrum. **68**, 647 (1997).
- [100] G. C. Idzorek and R. J. Bartlett, Proc. SPIE **3114**, 349 (1997).
- [101] 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).

- [102] 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).
- [103] 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).
- [104] 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).
- [105] R. E. Turner, O. L. Landen, P. Bell, R. Costa, and D. Hargrove, *Rev. Sci. Instrum.* **70**, 656 (1999).
- [106] D. L. Fehl, F. Biggs, G. A. Chandler, and W. A. Stygar, *Rev. Sci. Instrum.* **71**, 3072 (2000).
- [107] R. Byron Bird, Warren E. Stewart, and Edwin N. Lightfoot, *Transport Phenomena* (John Wiley and Sons, Inc., New York, 1960), pp. 437-443.
- [108] Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Academic Press, New York, 1966), Vol. I, pp. 192 - 215.
- [109] Y. T. Lee, *J. Quant. Spectrosc. Radiat. Transfer* **38**, 131 (1987).
- [110] *CRC Handbook of Chemistry and Physics - 81st Edition* , edited by David R. Lide (CRC Press, New York, 2000), pp. 10-175 to 10-177.
- [111] M. E. Cuneo (private communication).