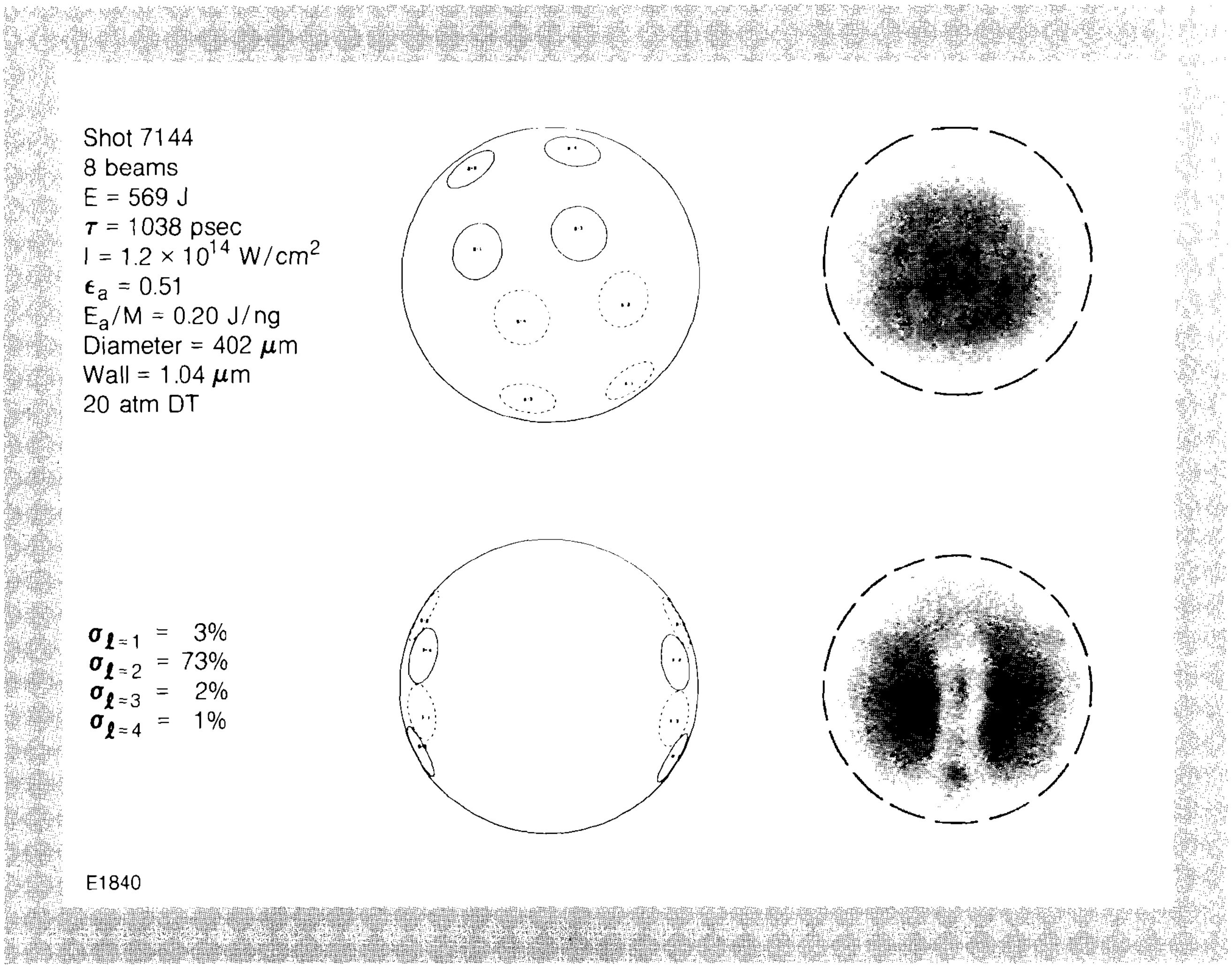

Fig. 14
Two views of the same target irradiated with 8 beams show that the core is pancake-shaped, due to the 73% $\ell = 2$ mode.

2.B Thermal Smoothing of Irradiation Nonuniformities in Laser-Driven Fusion

Spherical targets must be irradiated with a high degree of uniformity to drive the high-density implosions required for commercial energy production by laser fusion. Although completely spherical illumination can never be attained, some nonuniformities in laser energy-deposition on target can be smoothed by thermal conduction[1,2] as the heat is transported from the surface of laser deposition (at the critical density) to the ablation surface where the implosion is driven. The amount of thermal smoothing is influenced by inhibition of the thermal heat-flow into the target. Computer simulation of experiments and transport-theory have shown that the heat-flux is reduced relative to the classical Spitzer-Härm result, and that it saturates (or is "flux-limited") at a value far below the limit for freely streaming electrons.[3] The inhibition will have two competing effects on thermal smoothing: (1) the distance available for smoothing is reduced due to a smaller separation between the critical and ablation surfaces,[4] but (2) with less heat flowing radially into the target, more is available to flow laterally and to smooth nonuniformities. Using a model of steady-state ablation and thermal transport,[4] the second process is found to dominate. It reduces the laser intensity required for adequate thermal smoothing, substantially below the value estimated using classical transport. For even short-wavelength irradiation, this should permit laser operation below the intensity at which energetic electrons from resonance absorption would preheat the target and preclude a high-density compression.

The smoothing of a temperature nonuniformity is calculated here, first without the complication of hydrodynamic motion to demonstrate the effect of flux-limited transport; and this is followed by a more realistic treatment of the laser ablation process. For the simple model, steady-state heat-flow is assumed in the z-direction through a plasma of constant density with a temperature profile $T_o(z)$. A perturbing heat-source S' is imposed at $z = 0$, where $S' = S_o \cos(ky)\delta(z)$ and k is the perturbation wave number in the transverse (y) direction. For classical transport, the heat-flux is given by the Spitzer-Härm result,[7]

$$\bar{q} = -\varkappa T^{5/2} \; \nabla T \tag{3}$$

where T is the electron temperature and $\varkappa$ is the coefficient of thermal conductivity. The heat flux saturates at a value of q_{max}, usually parameterized in the form:

$$\bar{q}_{max} = -f\, n_e v_{th} T \;\; \nabla T/|\nabla T| \tag{4}$$

where the factor f (flux-limiter) is an adjustable parameter; n_e is the electron number density, and v_{th} is the electron thermal velocity ($\sqrt{T/m_e}$). Typically, values of f between 0.03 and 0.06 have been used to interpret experiments[3]—an order of magnitude below the value 0.65 for an isotropic, free-streaming gas. Using Eqs. (3) and (4), and $\nabla \cdot \bar{q} = S'$, the following equations are obtained for classical and flux-limited transport to first order in the perturbed temperature T' (where $T = T_o + T'$):

$$\frac{d^2}{dz^2}(T_o^{5/2}T') - k^2(T_o^{5/2}T') = 0 \tag{5a}$$

$$\frac{d}{dz}(\sqrt{T_o}\;T') + \tfrac{2}{3}k^2L(\sqrt{T_o}\;T') = 0. \tag{5b}$$

Here $z > 0$, $\nabla T_o/|\nabla T_o| = -1$, T' has $\cos(ky)$ y-dependence, and L is the unperturbed temperature scale-length, i.e., $L = T_o|dT_o/dz|^{-1}$. Solving Eqs. (5a) and (5b) for constant L, a comparison can be made between the different attenuations, $A = T'(z)/T'(0)$, of the temperature nonuniformity:

$$A \sim e^{-kz} \qquad \text{(classical)} \tag{6a}$$

$$A \sim e^{-Lk^2z\,2/3} \qquad \text{(flux-limited)} \tag{6b}$$

The important difference between classical and flux-limited thermal smoothing is the linear versus quadratic dependence on wave number. Both attenuations show increased smoothing for short-wavelength perturbations due to the proximity of hot and cold regions, but the distance required for smoothing decreases with k more rapidly for saturated flow, by a factor $\sim kL$. From the steady-state ablation model below, kL corresponds to ~ 4 for the nonuniformity characteristic of multiple, overlapping laser beams. For that example, flux-limited transport enhances the lateral heat-flow, and the required separation distance for smoothing is several times shorter than the classical result.

The thermal smoothing calculation for a realistic laser fusion model must include the effects of hydrodynamic motion and spherical geometry. To approximately treat the ablation process, an analytic, steady-state model by Max et al.[4] was used to obtain the spherically symmetric, unperturbed density (ρ_o) and temperature (T_o) profiles. The energy equation used for transport between the critical and ablation surfaces is:

$$\frac{5}{2}\rho\bar{v}\cdot\nabla T/\mu + \nabla\cdot\bar{q} = 0 \tag{7}$$

where μ is the average mass per particle; and terms on the order of $\mu v^2/T$ have been neglected as fluid flow inside critical density is highly subsonic for small flux limits. This model divides the region between the critical and ablation surfaces (at radii R_c and R_a) into two parts at the point R_s where the classical and flux-limited heat flows are equal. Between R_c and R_s the heat-flux is saturated while it is classical between R_s and R_a. In the flux-limited region:

$$T_o(r) = T_c(r/R_c)^{4/(1+M^2)} \tag{8}$$

where T_c is the temperature at critical density; and M is the Mach number (given approximately by $M \cong 14f$ for a CH_2 plasma).

Nonuniform laser deposition at the critical surface produces a perturbed temperature T'. Expanding T' in spherical harmonics,

$$T'(r,\theta,\phi) = \sum T_{\ell m}(r)\,Y_{\ell m}(\theta,\phi) \quad , \tag{9}$$

the perturbed energy transport equation in the flux-limited region becomes:

$$\frac{d}{dr}T_\ell - 2\frac{\ell(\ell+1)}{r^2}\frac{T_o}{dT_o/dr}T_\ell - 2\frac{\dot{m}'}{\dot{m}}\frac{d}{dr}T_o = 0 \tag{10}$$

where $\dot{m}$ is the mass ablation rate $4\pi r^2\rho_o v_o$. Only the subscript ℓ has been kept, since the equation is independent of the azimuthal index. The quantity $\dot{m}'$ is the perturbed mass ablation rate $4\pi r^2(\rho v_r)'$, and it can be evaluated by solving the full set of perturbed hydrodynamic equations.[10] However, for these calculations, the simplifying assumption was made that $\dot{m}'$ varies with perturbed temperature according to:

$$\dot{m}' = \xi\dot{m}T'/T_o \, , \tag{11}$$

with ξ being an adjustable parameter to determine the sensitivity of the results to $\dot{m}'$. This form gives the correct functional dependence of T′ for for $\ell = 0$ when $\xi = 1/2$ in the flux-limited region, and when $\xi = 5/2$ in the classical region. Over this range of ξ, the results below are relatively insensitive to $\dot{m}'$ for the dominant mode of irradiation nonuniformity.

Attenuation of temperature nonuniformities due to flux-limited transport is obtained by substituting Eqs. (11) and (8) into Eq. (10). For a small separation distance of the flux-limited region, $(\Delta R_s \equiv R_c - R_a)$ the relative temperature attenuation at R_s is:

$$\left[\frac{T_\ell}{T_o}\right]_s = \left[\frac{T_\ell}{T_o}\right]_c$$

$$\times\ \exp\left\{-\left[\ell(\ell+1)(1+M^2)/2 + 8(\xi - 1/2)/(1+M^2)\right]\frac{\Delta R_s}{R_c}\right\}, \qquad (12)$$

This expression displays the same quadratic dependence on wave number, $k \sim \ell$, as Eq. (6b). Temperature attenuation in the classical region was evaluated numerically and found to contribute less than 10%, for small flux-limiters ($f \leqslant 0.06$). Thus, Eq. (12) well approximates the total thermal smoothing.

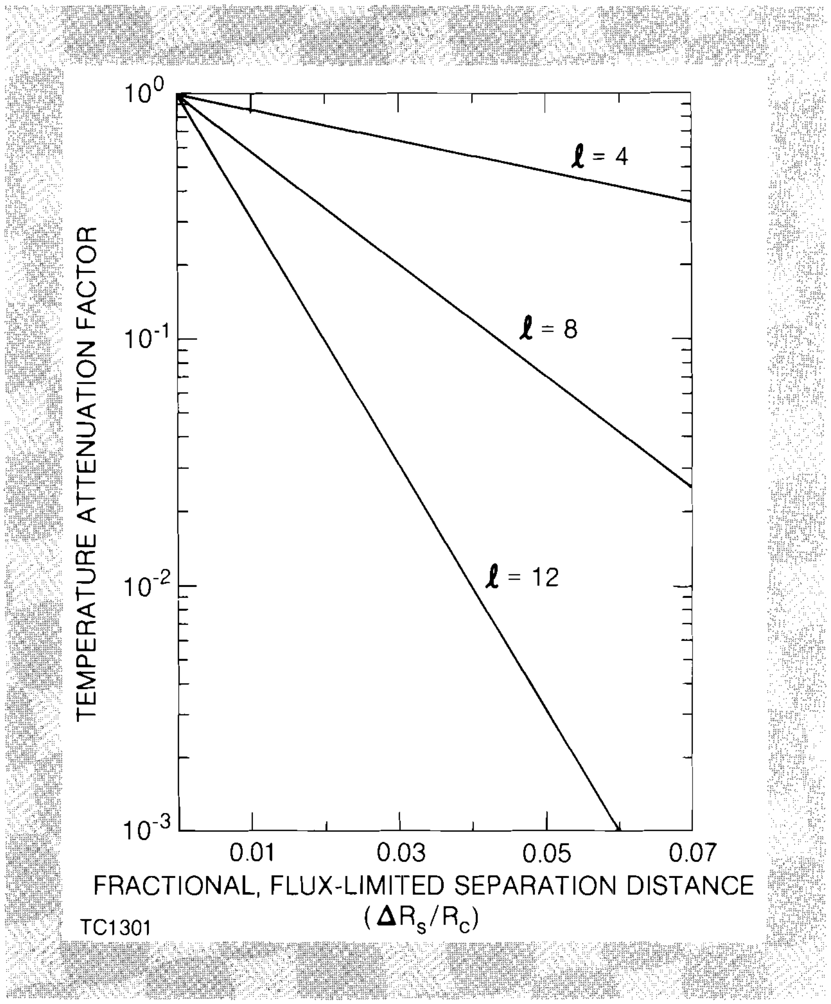

Fig. 15
Dependence of the nonuniform temperature attenuation on the radial separation distance of the flux-limited region for different spherical harmonic modes of the laser-deposition nonuniformity (Eq. 12). The parameter ξ was set to 1/2 so that the results are relative to zero attenuation for the $\ell = 0$ mode.

The temperature attenuation in the flux-limited region (Eq. 12) is shown in Fig. 15 as a function of the fractional separation-distance, $\Delta R_s/R_c$, for the modes $\ell = 4$, 8 and 12 with $\xi = 1/2$. Typically, for illumination with ~20 overlapping, uniformly-distributed laser beams, $\ell \sim 8$ is the dominant mode of nonuniformity,[8, 9] corresponding to a nonuniformity wavelength about equal to the target radius. (The dominant mode is related to the number of beams N approximately by $\ell \sim 2\sqrt{N}$.) For $\ell = 8$, a ten-fold attenuation is obtained when the separation distance of the flux-limited region is ~0.04 times the target radius. The relation between $\Delta R_s/R_c$ and the laser intensity is shown in Fig. 16 for different flux-limiters, at a laser wavelength λ of 0.35 μm and a target radius of 500 μm. For other radii and laser wavelengths, the intensity varies roughly as $R_c/\lambda^{3.5}$.

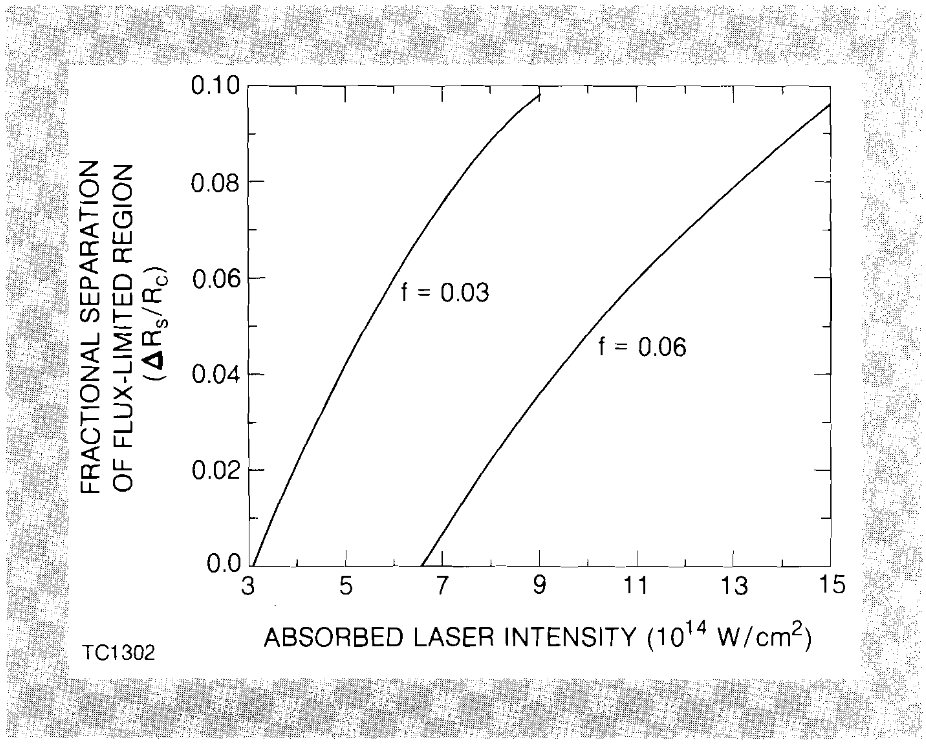

Fig. 16
Relation between the laser intensity and the radial separation distance of the flux-limited region for different flux-limiters. The results used the steady-state ablation model of Max et al.[4] for the target radius $R = 500$ μm and the laser wavelength, $\lambda = 0.35$ μm. For other values of R and λ, the laser intensity scales roughly as $I \sim R/\lambda^{3.5}$.

From Figs. (15) and (16), an order of magnitude smoothing is obtained at laser intensities around 5×10^{14} W/cm^2 for low flux-limits ($f \leqslant 0.06$). These irradiances are about ten times lower than the classical estimates.[11, 12] Although a small flux-limit is known to degrade the implosion-efficiency, it is seen here to have at least one positive feature—it can enhance the smoothing of laser nonuniformities.

The sensitivity of this result to the approximate treatment of $\dot{m}'$ (Eq. 11) is summarized in Table 2, which shows the intensity at which the $\ell = 8$ mode is attenuated ten-fold for $\xi = 0$, 1/2 and 5/2. The variation in intensities with ξ is relatively small compared to the effect of the flux-limiter, and this justifies, in part, the simplified treatment of $\dot{m}'$. In contrast, for $\ell = 2$, the perturbed mass ablation rate strongly affects the amount of temperature attenuation, and any results for this mode are very model-dependent.

These results suggest that adequate smoothing of the dominant $\ell = 8$ nonuniformity from ~20-beam illumination can occur at moderate laser

f \ ξ	0	1/2	5/2
0.03	5.2	4.7	4.2
0.06	8.2	8.0	7.5

TC1403

Table 2
The intensity (10^{14} W/cm^2) at which an $\ell = 8$ nonuniformity in laser energy deposition is attenuated for different flux-limiters, f, and parameters ξ from the perturbed mass ablation rate (Eq. 11). (The critical radius is 500 μm, and the laser wavelength is 0.35 μm.)

intensities and short-wavelengths. An important question not addressed here is the effect of laser illumination before a sufficient smoothing distance is established. This transient effect requires time-dependent calculations (presently in progress) of the full implosion process. A calculation[2] for one target design has shown that illumination nonuniformities imprint themselves on the target surface early in time and degrade the thermonuclear burn due to a nonspherical compression. During the implosion, the time at which thermal smoothing becomes effective depends on the details of electron energy-transport, as demonstrated above. A more detailed calculation would include the effects of non-local electron transport. Although the models used here only approximate the laser fusion process, they identify some of the important mechanisms that contribute to thermal smoothing. The results show that thermal smoothing depends on much more than the distance between the critical and ablation surfaces. Smoothing is crucially dependent on the size and temperature scale-length of the flux-limited region.

The reduction obtained in intensity required for thermal smoothing is particularly important for laser fusion experiments using short-wavelength illumination (such as $\lambda = 0.35$ μm from frequency-tripled Nd:glass lasers.) Present interest in using short-wavelength laser light is motivated by the high classical absorption and high hydrodynamic efficiency for imploding the target[13]; and the main drawback has been the prospect of poor thermal smoothing at moderate laser intensities.[12] Classical estimates placed the required intensity for smoothing near 10^{16} W/cm^2, at which point, high-energy electrons from resonance absorption are expected to preheat the target and degrade the implosion. By including the effects of flux-limited heat-flow, the required intensity for 0.35 μm illumination is reduced to about 5×10^{14} W/cm^2 where the generation of damaging suprathermal electrons should be negligible.

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