Section 2
PROGRESS IN LASER FUSION

2.A Characterization of Irradiation Uniformity on Spherical Targets

To achieve high energy production by laser fusion, deuterium-tritium fuel must be compressed to $\sim$ 1000 times its liquid density, and simultaneously heated above the ignition temperature ($\sim$ 5 keV) needed to sustain a thermonuclear burn.[1] The fuel is compressed and heated by depositing energy on the surface of a fuel-containing spherical target, causing surface material to be ablated, and driving the remainder of the target inward like a spherical rocket to implosion velocities greater than 10^7 cm/sec. For the method to be successful, a high degree of spherical convergence is required, placing severe constraints on the uniformity of energy deposition on the target surface. The level of nonuniformity in deposition that can be tolerated depends on the details of individual target designs; typically, an rms variation (σ_{rms}) of less than a few percent is required.[2]

Processes involved in direct laser drive are illustrated in Fig. 3. Shown schematically are two overlapping beams at tangential focus, each beam irradiating approximately half the target surface. The calculations below use examples with 24 and 32 such beams. Not shown in the figure, but included in our calculations, is the refraction of laser rays as they pass through the plasma atmosphere surrounding the target. After energy is deposited (which generally occurs close to the critical density), some of the nonuniformities in temperature are smoothed by thermal conduction[3,4] as heat is transported inward to the ablation surface where the implosion is driven. The shorter-wavelength nonuniformities are more easily smoothed due to the prox-

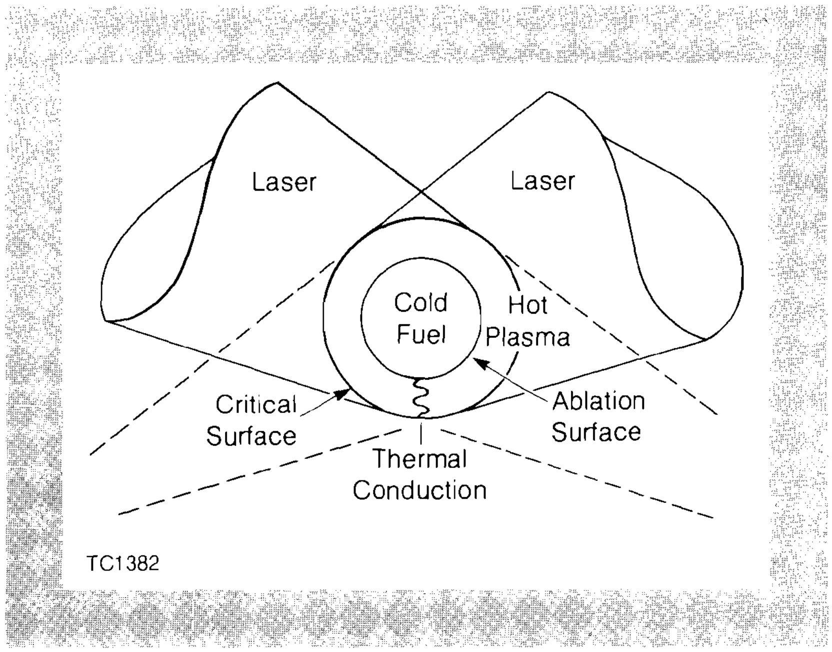

Fig. 3
A high degree of irradiation uniformity can be achieved by overlapping laser beams. The laser light is refracted in the plasma atmosphere surrounding the target, with the majority of energy deposited near the critical density. Heat is then transported inward to the ablation surface where the implosion is driven. Some smoothing of nonuniformities in energy deposition can occur over the distance of heat transport.

imity of the hotter and colder regions. Thus, in examining the uniformity of energy deposition, we place considerable emphasis on calculating the spatial wavelengths of nonuniformities in addition to their magnitudes. This leads us to consider a spherical-harmonic decomposition of the laser-irradiation nonuniformity.

The uniformity of energy deposition in the target is calculated by tracing laser rays through the plasma atmosphere according to geometrical optics, and depositing energy along each ray trajectory by inverse bremsstrahlung. The calculation is greatly simplified by using beams with identical, azimuthally symmetric intensity profiles and perfectly spherical targets. Then the deposition pattern for only one beam need be calculated, and results for the other beams are obtained by rotation. To analyze the spatial variations of nonuniformities, the energy-deposition pattern is decomposed into spherical harmonics. The nonuniformity wavelength λ in each spherical-harmonic mode is related to the mode number ℓ approximately by:

$$\lambda = 2\pi R/\ell,$$

where R is the target radius. Thus $\ell = 6$ corresponds to $\lambda \simeq R$.

A useful measure of the illumination nonuniformity is the rms deviation defined as

$$\sigma_{rms} = \left\{ \frac{1}{4\pi} \int |E(\hat{r}) - \langle E \rangle|^2 \, dS \right\}^{1/2} / \langle E \rangle, \tag{1}$$

where $\langle E \rangle = \int E(\hat{r}) dS / 4\pi$, $E(\hat{r})$ is the total laser energy (summed over all beams) deposited between critical and 0.4 times critical density at an angular position determined by the unit vector $\hat{r}$, and dS is a surface element at $\hat{r}$. The energy-deposition pattern $E(\hat{r})$ is decomposed into Legendre polynomials and written as the sum of contributions from the individual beams (with index k):

$$E(\hat{r}) = \sum_{\ell} \frac{2\ell+1}{2} E_{\ell} \sum_{k} W_k P_{\ell}(\hat{r}\cdot\hat{\Omega}_k) . \tag{2}$$

Here all beams are assumed to have the same azimuthally symmetric profiles around their beam axes $\hat{\Omega}_k$, but the possibility of different energies, W_k, is allowed. The product $\hat{r}\cdot\hat{\Omega}_k$ is the cosine of the angle between a beam axis and an arbitrary unit vector $\hat{r}$ (see Fig. 4).

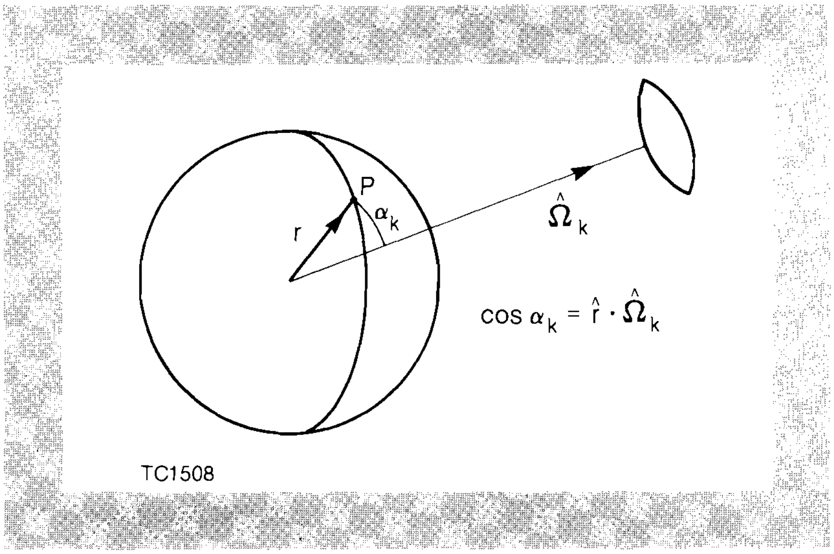

Fig. 4
The energy deposited at a point P is calculated by summing over a number of beams with identical azimuthally symmetric profiles. The contribution from beam k depends only on the angle α_k between $\hat{r}$ and the beam axis and on the distance r from the target center.

Substituting Eq. (2) into Eq. (1) and using the orthogonality property of Legendre polynomials, σ_{rms} can be written explicitly in terms of the contribution from each ℓ-mode:

$$\sigma_{rms} = \left\{ \sum_{\ell \neq 0} \sigma_{\ell}^2 \right\}^{1/2} \tag{3}$$

where σ_{ℓ} is[5]:

$$\sigma_{\ell} = |E_{\ell}/E_0| \left\{ (2\ell+1) \sum_{k,k'} P_{\ell}(\hat{\Omega}_k\cdot\hat{\Omega}_{k'})\, W_k W_{k'} / W_T^2 \right\}^{1/2}, \tag{4}$$

and where W_T is the total energy in the beams: $W_T = \sum W_k$.

Another measure of nonuniformity is the peak-to-valley variation $\Delta E/E$. We use σ_{rms} here because it can be expressed analytically [Eq. (4)], and the different factors can be examined directly. In contrast, the peak-to-valley variation requires a computer search over the target surface to find the extreme values of E. Typically, $\Delta E/E$ was found to be 3 to 5 times larger than σ_{rms} for the different cases examined.

The quantity σ_{ℓ} [Eq. (4)], characterizing the contribution of each mode to the overall nonuniformity, is factored into two terms:

1) The first term, $|E_{\ell}/E_0|$, is the energy-deposition pattern from a single beam which is determined by the focal position, intensity profile across the beam, lens f-number, and the density and

temperature profiles in the target plasma.

2) The second factor contains all the geometrical information about the laser system related to the number and orientation of the beams, and the energy balance between beams.

Clearly, the nonuniformity in a mode will vanish if conditions are found such that either factor is zero.

Two general results may be obtained just from the geometrical symmetry of the laser system, independent of the details about beam overlap or the laser absorption process. One is that all odd-order values of σ_ℓ vanish for any system with opposing beams and perfect beam energy balance. This occurs because the irradiation patterns on both sides of any great circle around the target are the same. A second result is that if N beams are uniformly distributed, then the lowest dominant mode of nonuniformity is given approximately by:

$$\ell = \pi \sqrt{N}/2.$$

As an example, for the 32-beam system discussed below, the geometrical term essentially eliminates all modes below $\ell = 10$. The magnitudes of the modes 10 and above are affected by the single-beam factor, which can even be "tuned" to eliminate some of these modes by means of profile shaping and focus adjustment.

Uniformity Results

The effects of specific laser-target conditions are illustrated here using as examples: (1) the 24-beam OMEGA laser system, and (2) a 32-beam system ("truncated" icosahedron) comprised of beams whose axes penetrate the centers of the 20 faces and the 12 vertices of an icosahedron. The first illustrates the uniformity potentially available with a currently operating laser system. The second illustrates that high uniformity can be attained even with high-f-number optics as required for future fusion reactors. (A high f-number is required to keep the final optical elements as far from the target explosion as possible.[6])

In our calculations, we have considered the following variables: (1) radial laser intensity profile, (2) focus, (3) beam number and configuration, (4) plasma density profile in the target, (5) energy balance between beams, and (6) beam-target alignment. Beam imbalance and laser-target misalignment are found[5] to be the main contributors to the long-wavelength modes ($\ell \leq 4$), and the remaining variables are responsible for shorter-wavelength nonuniformities. We calculate σ_{rms} from Eqs. (3) and (4) using the first 40 modes.

All of the examples given here use a 500-μm-radius target. The plasma atmosphere is at a temperature of 3 keV, with a distance of 10 μm between the critical and one-third-critical density radii and an exponential density profile with a scale length of 50 μm beyond. Such double-scale-length profiles are obtained in computer simulations of high-intensity laser irradiation with flux-limited heat flow.[7] All the energy deposited in the short-scale-length (10-μm) region should contribute about equally to the implosion as this region covers a range of just a few electron mean free paths. However, the energy deposited beyond one-third critical density can be at a relatively long distance from the ablation surface and should be less effective in driving the target. Since we are interested in drive uniformity, this distant energy deposition is not included here in the calculation of σ_{rms} in order to obtain a conservative estimate. This energy represents about 15% of the total and is relatively uniformly distributed; when it is included, σ_{rms} is reduced by a few percent.

The rms variation in energy deposition for the 24-beam system is shown in Fig. 5 as a function of focus, for three different radial beam

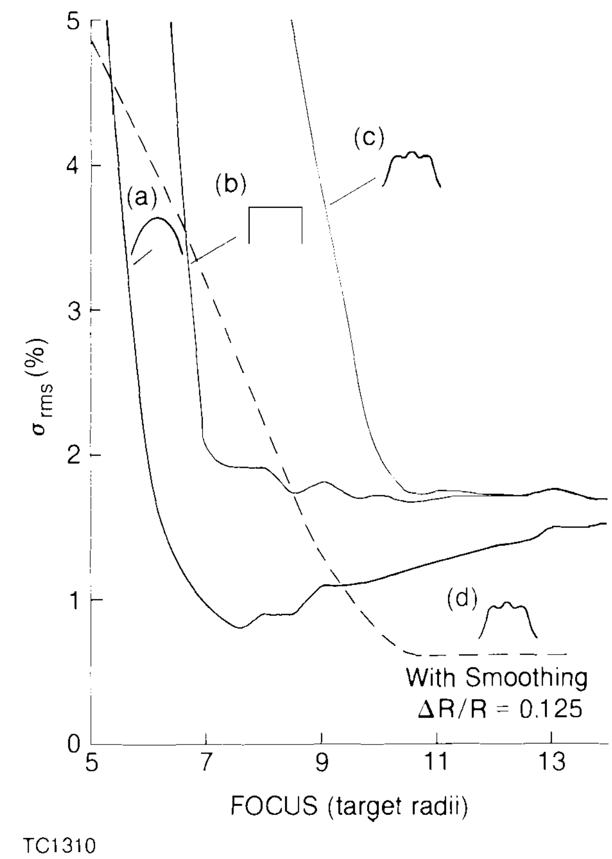

Fig. 5
Intensity nonuniformity (rms) for the 24-beam OMEGA system, as a function of focus, for three laser-beam intensity profiles: (a) quadratic, (b) flat-top, and (c) a recent experimentally obtained profile. In all cases an "asymptotic" nonuniformity level of 2% is achieved by defocusing the beam beyond tangential focus (8 target radii behind the target here).

profiles. Two of the profiles are: (1) quadratic, $I = I_o(1\text{-}r^2/r_o^2)$ and (2) flat-top, $I = I_o$ for $r < r_o$. The third is a recently obtained equivalent-target-plane profile from the GDL laser system,[8] shown in Fig. 6. When these three profiles are compared, the main qualitative result is that the highest uniformity ($\sigma_{rms} < 1\%$) is obtained from a smoothly varying profile without sharp edges. The ideal quadratic shape need not be produced directly by the laser, but can be created in the target plane by the final focusing elements. Note that beyond tangential focus (corresponding to 8 target radii, 8R, behind the target in Fig. 5) the uniformity is insensitive to the beam shape. All profiles converge to

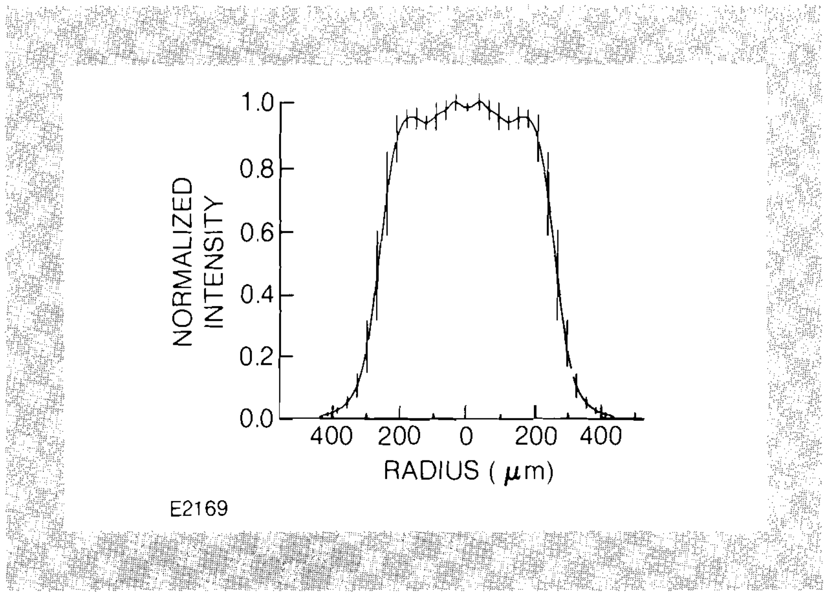

Fig. 6
Azimuthally averaged experimental intensity profile used for uniformity calculations. The vertical bars indicate the rms azimuthal variation around the average.

the same result ($\sigma_{rms} \sim 2\%$) because only the central part of the beam, which is similar for these profiles, reaches the target; the outer part is refracted. This 2% nonuniformity level does not require profiles very different from those presently available (although deviations from azimuthal symmetry have not yet been considered). The penalty for energy loss by refraction is relatively small in this example: the fractional absorption decreases by about 15% in defocusing from 7R to 12R.

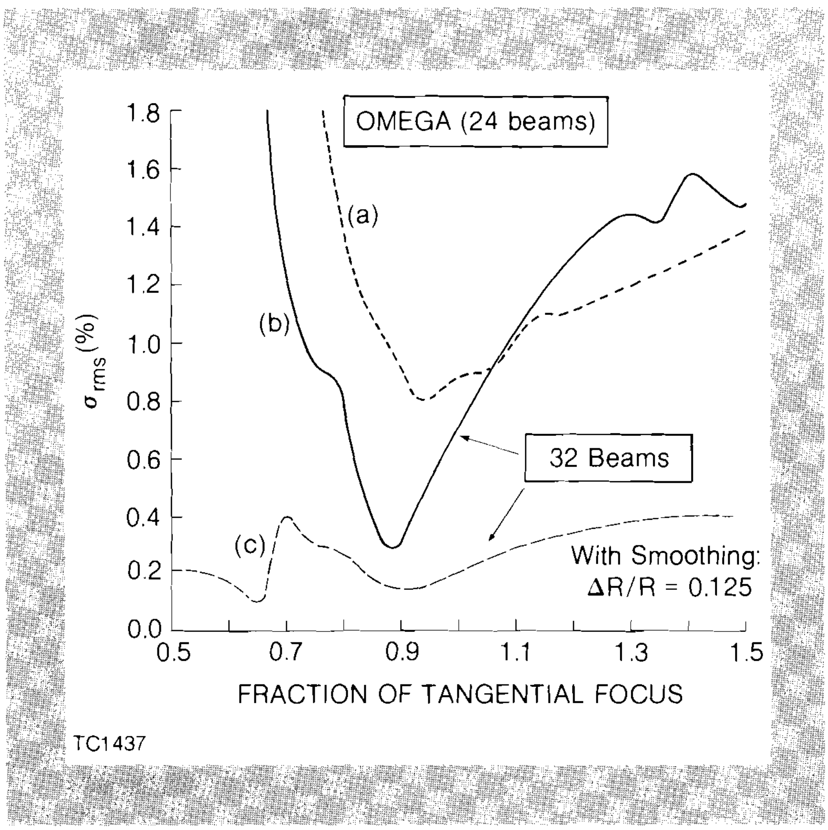

Fig. 7
Comparison of rms nonuniformity between (a) the 24-beam (f/4) laser system and (b) the 32-beam (f/20) system using a quadratic beam profile. Including moderate thermal smoothing (corresponding to $\Delta R/R = 0.125$), curve (c) is obtained for the 32-beam system.

The 24-beam (f/4) system is compared with the 32-beam (f/20) system in Fig. 7 using the quadratic profile. (Here the focus parameter should be multiplied by twice the f-number to obtain target radii; tangential focus equals 1 in these units.) There is a decrease in nonuniformity by a factor of 2 over a small focal range for the 32-beam system. This improvement is the result of higher geometrical symmetry, and it is particularly impressive since the solid angle subtended by the lenses is only 0.5%, compared with 15% for the 24-beam system.

This high degree of uniformity ($\sigma_{rms} < 1\%$) is obtained over a limited focal region. It is difficult to remain in this region during the entire laser-fusion implosion, as the focus parameter will be constantly changing. For short-wavelength irradiation the critical surface moves inward, so that the focal length, expressed in units of the instantaneous target radius, increases. One strategy is to focus so that the highest uniformity is obtained initially. At later times the nonuniformity will increase, but the target plasma will by then have expanded, and additional thermal smoothing of the short-wavelength nonuniformities may then be permitted.

Thermal Smoothing

While the calculations presented above give the nonuniformity in the absorption region, it is the nonuniformity at the ablation surface which determines the implosion nonuniformity. Improved symmetry at the ablation surface will result from thermal smoothing, an effect which may be estimated by multiplying each of the σ_ℓ of Eq. (4) by a classical attenuation factor[9] of $\exp(-\ell\Delta R/R)$, where $\Delta R/R$ is the fractional separation of the critical and ablation surfaces. Clearly the short-wavelength nonuniformities (large ℓ) will be attenuated the most. A value of $\Delta R/R = 0.125$, characteristic of irradiation with 0.35-μm light, has been used; this leads to significant attenuation of modes with $\ell > 8$.

Typical results including smoothing are shown in the dashed curves of Figs. 5 and 7. In Fig. 5, σ_{rms} is reduced to below 1% for focusing beyond 10R for the experimental beam profile. Near-term experiments may therefore proceed with a relatively high uniformity, in parallel with the development of a beam-shaping capability. For future experiments with a 32-beam system and a quadratic beam profile, the dashed curve (c) of Fig. 7 shows that moderate thermal smoothing will lead to values of σ_{rms} below 0.4% over a broad focusing range.

Summary

The uniformity of laser-energy deposition on laser-fusion targets has been analyzed using a spherical-harmonic decomposition of the deposition pattern. It has been found that the contribution of each mode to the nonuniformity can be factored into two terms, one depending only on the geometrical orientation of the laser beams, and the other depending on details of the ray trajectories for only a single beam. The geometrical symmetry of the laser system effectively eliminates the longer-wavelength nonuniformities, and the shorter spatial wavelengths may be partially "tuned out" by varying the focus of the beam and its radial intensity profile.