# Irradiation Uniformity for High-Compression Laser-Fusion Experiments

Various techniques are being used to achieve the high irradiation uniformity required for direct-drive, laser-fusion experiments on the OMEGA laser system. These techniques are directly applicable to the National Ignition Facility (NIF) being built at the Lawrence Livermore National Laboratory. The combination of two-dimensional smoothing by spectral dispersion (SSD),[1–3] distributed phase plates (DPP's),[4,5] polarization smoothing (DPR's),[6,7] and beam overlap should be sufficient to reach the rms level of 1% or less when the laser intensity has been averaged over a few hundred picoseconds. Of these, SSD is the dominant mechanism for reducing the nonuniformity.

The SSD beam-smoothing technique produces uniform laser beams in a time-averaged sense. The level of uniformity that can be achieved is determined by two factors: bandwidth and spectral dispersion. The amount of bandwidth determines the rate of smoothing, and the amount of spectral dispersion determines the level of uniformity that can be achieved (as well as the longest spatial wavelength of nonuniformity that can be smoothed). Frequency-tripled glass lasers (such as OMEGA and the NIF) place constraints on both bandwidth and spectral dispersion. Until recently, high-efficiency frequency tripling of laser light was limited to a bandwidth of 3 Å to 4 Å in the IR. Recent calculations and experiments[8,9] have shown that this bandwidth can be increased by a factor of 3 to 4 by using a second tripling crystal, resulting in ~1 THz in the UV, with a ~70% tripling efficiency. Second triplers will be installed on OMEGA during 1999.

The spectral dispersion of the bandwidth on OMEGA has been limited by the laser spatial-filter pinholes to an angular spread of ~50 $\mu$rad (relative to the output of the system). This will be increased on OMEGA during 1999 to accommodate asymmetric SSD dispersion, with 100 $\mu$rad in one direction and 50 $\mu$rad in the other. Polarization smoothing will provide an additional 50 $\mu$rad, resulting in a total angular spread of 100 $\mu$rad in each direction.[10] With these laser modifications, it is expected that the levels of uniformity required for high-compression experiments on OMEGA will be achieved. The rms nonuniformity will drop below 1% after a smoothing time of ~250 ps. These same uniformity techniques are directly applicable to the NIF and will result in even higher levels of uniformity because of the larger number of beams (192 versus 60).

With the angular divergence of the beam that will be achieved on OMEGA during 1999, all spatial wavelengths of nonuniformity of concern for ICF will be smoothed. The longest wavelength of nonuniformity that can be smoothed by SSD and polarization smoothing can be estimated in the following way: Both SSD and DPR's smooth nonuniformities by shifting the speckle pattern produced by a phase plate. Two overlapped speckle patterns that have been shifted by a distance $S$ will exactly smooth a nonuniformity of spatial wavelength $2S$. The maximum speckle shift is given by $S_{\max} = F\Delta\theta$, where $F$ is the focal length and $\Delta\theta$ is the beam angular divergence; thus, SSD can smooth spherical harmonic modes of nonuniformity down to $\ell_{\text{cut}} = 2\pi R/(2S_{\max})$, where $R$ is the target radius. Using OMEGA parameters $F = 180$ cm, $R = 500$ $\mu$m, and $\Delta\theta = 90$ $\mu$rad, we have $\ell_{\text{cut}} \sim 10$, which is well below the modes of concern for seeding hydrodynamic instabilities. For the NIF, the same angular divergence will produce essentially the same value of $\ell_{\text{cut}}$ since both the focal length and the target radius will be 3.5 to 4 times larger than for OMEGA.

The mathematical formalism describing 2-D SSD is presented in Ref. 2. We can use the approximate asymptotic expression for the SSD reduction factor [Eq. (20) in Ref. 2] to confirm the above estimates for the longest wavelength of nonuniformity that can be smoothed by SSD. First, this equation is modified to include the contribution of polarization smoothing as follows: Let the polarization dispersion be in the $y$ direction, with $\Delta_p$ the spatial separation between $e$ and $o$ rays in the target plane. Then the superposition of the $e$ and $o$ intensities is $\frac{1}{2}\left[I\left(x, y+\Delta_p/2\right)+I\left(x, y-\Delta_p/2\right)\right]$. For the asymptotically smoothed intensity, the SSD reduction factor $R_{ij}^{p}$ is

$$R_{ij}^{p} = J_0\left(6\delta_1 \sin\tfrac{1}{2}k_i\Delta_1\right)\times J_0\left(6\delta_2 \sin\tfrac{1}{2}k_j\Delta_2\right) \times\cos\left(\tfrac{1}{2}k_j\Delta_p\right) \quad (1)$$

for spatial modes $\left(k_i, k_j\right)$ in the $(x, y)$ directions. The factor $6\delta_{1,2}$ is the number of spectral modes for each direction of SSD (after frequency tripling), and $\Delta_{1,2}$ is the separation of the modes. The first zero of the first Bessel function will determine the longest wavelength for which there is substantial smoothing in the $x$ direction. Expanding the "sin" function for small $k$ and using $S_1 = 6\delta_1\Delta_1$ as the maximum spectral shift, the argument of the Bessel function becomes $\frac{1}{2}\ell S_1/R$, where $\ell$ is the effective spherical harmonic mode number ($\ell = k \times R$). This gives $\ell_{cut}$ = 15, where $J_0\left(\frac{1}{2}\ell_{cut} S_1/R\right)=0$, which is a little higher than the rough estimate above.

In the perpendicular direction, there is smoothing from both the spectral dispersion and the polarization spread. For the strategy being implemented on OMEGA, the spectral angular spread in this direction is half the spread in the other direction $\left(S_2 = \frac{1}{2}S_1\right)$ in order to keep the laser pinholes as small as possible. The total speckle shift in this direction is then doubled by means of the polarization shift for $\Delta_p = S_2$. With these parameters, the "cos" term in Eq. (1) gives the lowest value of $\ell$ for which $R$ is zero in the $y$ direction, namely $\ell \approx 20$. Of course there is still some smoothing below $\ell = 20$.

The smoothing of long-wavelength nonuniformities can be seen in the full time-dependent calculation shown in Fig. 77.13. Shown is the calculated rms nonuniformity for 60 overlapping beams on a spherical target (using the OMEGA irradiation geometry). The nonuniformity for each individual beam was calculated from the time-dependent SSD equations in Ref. 2, and the result was projected onto the sphere. The first image shows how the nonuniformity spectrum has decreased after 500 ps of smoothing for 500 modes, with 1 THz of bandwidth. [Plotted is the rms nonuniformity $\sigma_\ell$ of the spherical harmonic mode $\ell$, defined such that the total rms nonuniformity is $\left(\Sigma\sigma_\ell^2\right)^{1/2}$]. The second image shows the spectrum for the first 50 modes, which is a region of particular concern for direct-drive laser fusion.

We first note that even without SSD, the nonuniformity in the very low-order modes ($\ell$ = 11 to 30) is very small, 1%. After 500 ps of smoothing, this has been reduced to 0.15%. Smoothing is occurring for modes that are about a factor of 2 lower than indicated in the results of Rothenberg.[3] The reason is that this calculation has used twice the angular divergence of Rothenberg; he limited the angular spread of the beam to be 50 $\mu$rad. We have increased the spread to 100 $\mu$rad in one direction and doubled the 50-$\mu$rad spread in the second direc-

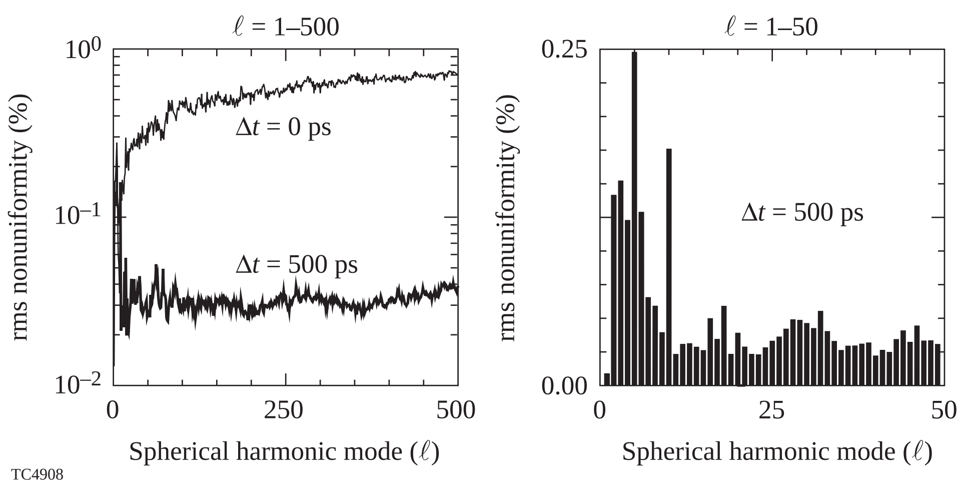


Figure 77.13
The reduction in nonuniformity produced by SSD on OMEGA when the intensity is averaged over 500 ps, for a bandwidth of 1 THz and a total angular spread of 100 $\mu$rad. The IR bandwidths for the two modulators are 2.1 Å and 10.2 Å with modulation frequencies of 8.8 GHz and 10.4 GHz.

tion by means of the polarization wedge. This is consistent with the above analysis showing that when the total speckle shift is about 15% of the target diameter, modes below $\ell = 15$ are smoothed. These calculations have included the effect that the envelope, as well as the speckle, is shifted. The smoothing effect is more dramatic for higher-order modes; for $\ell = 31$ to 500 the nonuniformity is reduced from 13% to 0.6% rms.

The second image in Fig. 77.13 shows details of the long-wavelength nonuniformity structure after 500 ps of smoothing (note that the vertical scale has changed). It is now more clearly seen that modes down to $\ell = 11$ have been smoothed. The spike at $\ell = 10$ as well as the additional nonuniformity at lower $\ell$ is the result of how the 60 beams overlap on the spherical target; it is not the result of structure on an individual beam. This form of nonuniformity can be reduced by a careful choice of the radial beam profile that is generated by the phase plate. These calculations have used the sinc$^2$ profile that is generated by square phase-plate elements (and modified by SSD), with the target boundary near the 5% intensity contour.

The discussion after Eq. (1) shows that the asymptotic level of smoothing reached by SSD in the low-order modes depends only on the size of the speckle deflections: $S_1$, $S_2$, and $\Delta_p$. (This is valid over the range of wavelengths for which the "sin" functions in that equation can be expanded to first order.) The amount of time required to reach this level can be decreased, however, by increasing the number of color cycles.[1–3] This occurs because the longer wavelengths of nonuniformity are produced by interference between phase-plate elements that are relatively close together. By increasing the number of color cycles, the relative phase between close phase-plate elements varies more rapidly, and faster smoothing occurs. This is at the expense, however, of reduced smoothing for very short wavelengths of nonuniformity (high $\ell$) produced by interference between more-distant phase-plate elements.

One example of the effect of three color cycles compared to one cycle is shown in Fig. 77.14. This corresponds to an intermediate case that might be examined on OMEGA before the implementation of 1 THz of bandwidth. Both cases in Fig. 77.14 correspond to a bandwidth of 0.3 THz with one color cycle and a polarization wedge in one of the directions. In the second direction, one case has one color cycle and the other has three, produced by a threefold increase in modulation frequency. The results are given after 250 ps of smoothing. (The total nonuniformity is about 1.7% rms.) For three color cycles, the nonuniformity in modes 50 to 200 has been reduced by about 50%, at the expense of some increased nonuniformity above $\ell = 300$. It is believed that this shift in the nonuniformity spectrum is beneficial, as modes below $\ell = 200$ are considered to be the most dangerous. After about 1 ns of smoothing time, however, both examples show about the same asymptotic level of nonuniformity for the long wavelengths.

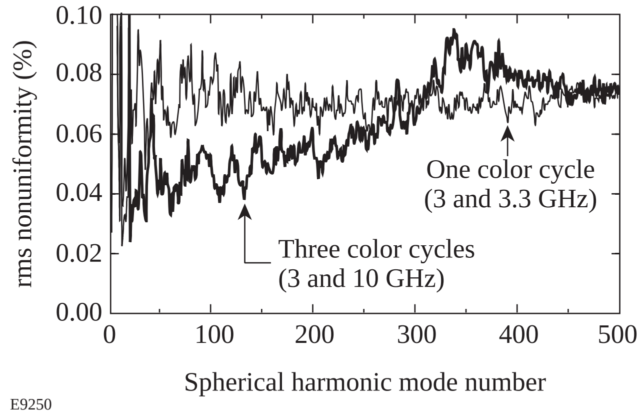


Figure 77.14
By increasing the number of color cycles, long wavelengths of nonuniformity can be reduced at a faster rate. The nonuniformity spectrum with 0.3 THz of bandwidth and 250 ps of smoothing time is compared for one and three color cycles. The bandwidths in both cases were 1.5 × 3 Å. For one color cycle the modulation frequencies were 3 and 3.3 GHz. For three color cycles (in one direction) the 3.3-GHz modulator was replaced by a 10-GHz modulator.

Finally, in Fig. 77.15 we compare the effects of the different improvements in uniformity that are planned for OMEGA during 1999. The current SSD configuration consists of IR bandwidths of 1.25 × 1.75 Å with electro-optic (EO) modulators of 3 and 3.3 GHz. The spectral divergence is less than 50 $\mu$rad. A small number of polarization wedges are available for planar experiments. A full set of 60 wedges will be installed during 1999 for spherical experiments. At the same time, the bandwidth will be increased to 1.5 × 3.0 Å with the resulting spectral/polarization dispersion being ~100 $\mu$rad in each direction. During the latter half of the year, one of the EO modulators will be replaced by a 10-GHz modulator and the IR bandwidth increased to ~12 Å, resulting in a UV bandwidth of ~1 THz.

The improvements in irradiation nonuniformity planned for the OMEGA laser during 1999 will reduce the rms nonuniformity to less than 1% when the intensity is averaged over 300 ps. The total nonuniformity in the long-wavelength nonuniformities (spherical harmonic modes 11 to 30) can be smoothed to levels below 0.15%. This is being accomplished by the addition of three new features to the laser: (1) Second

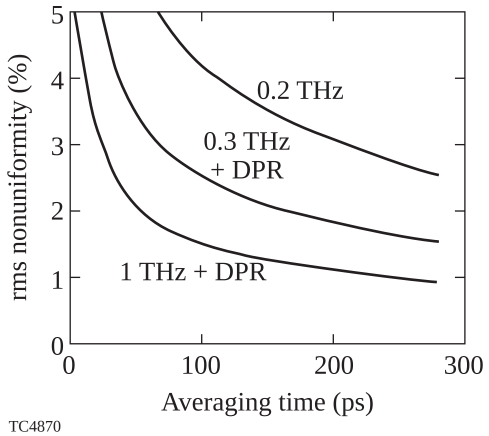


Figure 77.15
The rms nonuniformity as a function of time for the current SSD configuration on OMEGA and the upgrades planned for 1999, including the effect of multiple-beam overlap on a spherical target in the 60-beam geometry. Spherical harmonic modes up to $\ell = 500$ have been considered with no additional smoothing assumed in the plasma atmosphere around the target. The top curve shows the current level of irradiation uniformity. The middle curve corresponds to a higher bandwidth in one direction and the inclusion of polarization smoothing. The bottom curve is the result for 1 THz of UV bandwidth and polarization smoothing.

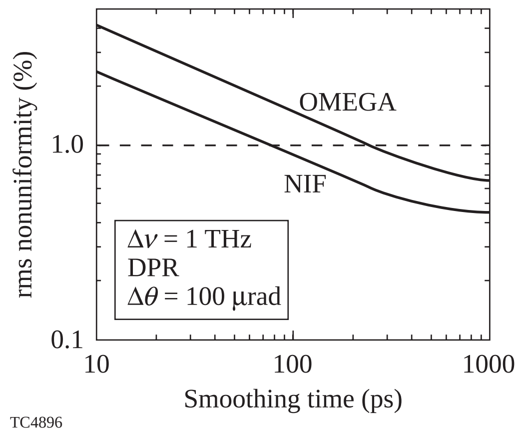


Figure 77.16
The rms nonuniformity as a function of time for the NIF and for OMEGA, assuming 1-THz bandwidth and polarization smoothing. All spherical harmonic modes between 5 and 500 are included.

triplers will allow the high-efficiency tripling of 3 to 4 times the current bandwidth. This will decrease the smoothing time by the same factor. (2) Polarization wedges added to all 60 beams will instantaneously reduce nonuniformity by $\sqrt{2}$ and double the maximum shift of speckle patterns on the target. (3) An increase in laser-pinhole size will double the allowed spectral spread in one direction from 50 $\mu$rad to 100 $\mu$rad. (The angular spread in the perpendicular direction will remain 50 $\mu$rad.) The combined effect of the polarization spread and the increased spectral spread will be a factor-of-2 reduction in the largest spherical harmonic mode of nonuniformity that can be smoothed, and a reduction in the asymptotic value of nonuniformity by almost the same factor.

These uniformity improvements are directly applicable to the NIF. As with OMEGA, the current pinhole specification for the NIF limits the angular spread of the beam to 50 $\mu$rad. The NIF optical design should be examined to determine if the pinhole can be opened further for direct-drive experiments as is being done on OMEGA. Using essentially the same SSD configuration as OMEGA, including polarization smoothing and dual-tripler frequency conversion, even higher uniformity will be achievable on the NIF due to the larger number of beams (192 versus 60). A comparison between NIF and OMEGA uniformity is shown in Fig. 77.16. It is expected that this smoothing rate and the level of uniformity should be adequate for direct-drive ignition experiments.

## ACKNOWLEDGMENT

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