2.B Strategies for Ultra-High Laser Uniformity Using Zero-Correlation Phase Masks

Laser fusion requires highly uniform target irradiation to minimize development of hydrodynamic instabilities. Random phase plates[1,2] have been used routinely to provide a uniform far-field intensity envelope on target that is relatively independent of the input-beam profile. However, superposed on this envelope is highly modulated speckle from the interference among different phase-plate elements. Once a sufficiently large plasma atmosphere has developed around the target, the effects of speckle will be greatly reduced, as nonuniformities in laser-energy deposition will be smoothed by thermal conduction within the target. However, prior to that stage, the irradiation nonuniformities will imprint themselves on the target surface. The resulting surface deformation will act as a "seed" for growth of the Rayleigh-Taylor hydrodynamic instability that can preclude a high-density compression and high thermonuclear yield. Beam-smoothing techniques[3,4] have been developed to change the speckle pattern in time and produce a relatively smooth, time-averaged intensity profile. The main issue is whether the intensity modulations are reduced on a fast-enough time scale to prevent significant beam imprinting on a target in the early stages of irradiation.

Uniformity during the onset of irradiation is more easily addressed for laser configurations such as the OMEGA Upgrade,[5] for which the early-time "foot" of the pulse is spatially separated from the main part of the pulse. (For the OMEGA Upgrade, the foot pulse will contain less than 10% of the pulse energy. It will co-propagate with the main pulse through the same beamlines but occupy only the inner 20%–30% of the aperture radius.) Because of the physical separation between these parts of the pulse, it is possible to apply additional uniformity techniques to the foot pulse that might not be appropriate for the larger, more-energetic main portion of the beam. The strategies discussed here have been specifically designed for the foot pulse to achieve the higher levels of uniformity required at the onset of target irradiation.

To obtain the higher uniformity, we have developed a technique for choosing the phase-plate elements (in combination with polarization rotation) such that the speckle intensity modulations, normally produced from a phase plate, are instantaneously zero, at least in the limit of plane-wave, near-field irradiation. Such phase plates are referred to here as zero-correlation masks (ZCM). For a beam with small phase aberrations, the far-field intensity fluctuations around the envelope will also be small. However, for large phase aberrations the resulting speckle modulation will be the same as for a random phase plate. Some strategies for reducing the sensitivity of a ZCM to phase aberrations and to other near-field imperfections will be discussed.

Zero-Correlation Mask

A key ingredient for forming a ZCM is polarization rotation across one-half of the phase-plate elements. The interference patterns produced by each of the polarization directions are chosen to be complementary, such that the intensity peaks of one exactly fill the valleys of the other. More formally, the phases are distributed such that the sum of the autocorrelation functions for the two degrees of polarization are exactly zero for each spatial wavelength of nonuniformity. An algorithm for generating ZCM's is described in Ref. 6.

A comparison between the far-field intensity patterns for a random phase plate and a ZCM is shown in the computer simulations of Figs. 54.4(a) and 54.4(b). Both cases used a 32×32 phase plate with phase elements of either 0 or π. Both plates were uniformly illuminated and had a 90° polarization rotation across one-half of the elements. The only difference is that in Fig. 54.4(a) the phases were chosen randomly, and in Fig. 54.4(b) the phases were chosen according to the ZCM algorithm of Ref. 6.

The smooth intensity profile calculated for the ZCM in Fig. 54.4(b) requires a very delicate balance among all phase differences across the mask. The calculation assumed ideal illumination conditions such as no spatial variation of phase or amplitude across the phase plate, perfect focusing of the beam, and high-contrast polarization rotation. Large deviations from ideal conditions will destroy the delicate phase balance and introduce speckle structure, similar to Fig. 54.4(a). For small variations from ideal conditions, the modulation of the speckle is proportional to the near-field variation. For instance, when the phase aberration is less than a few tenths of a wave, the rms intensity variation around the smooth envelope is found to be proportional to the rms phase variation of the aberration.

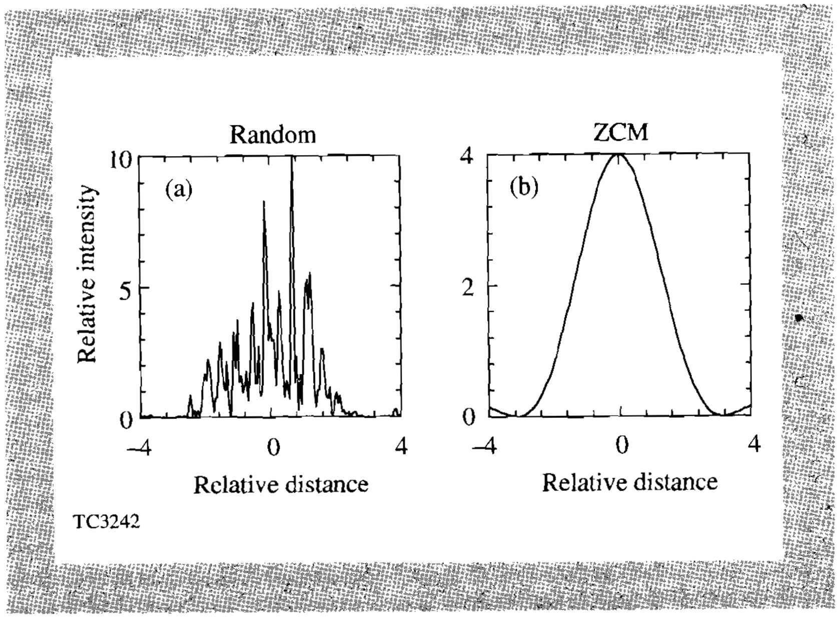

Fig. 54.4
Far-field intensity profile for (a) a random phase plate with a polarization rotator and (b) ZCM. Both are 32×32 phase plates with plane-wave, near-field irradiation.

When a ZCM is used instead of a random phase plate, there is new motivation to construct and maintain high-quality laser beams, i.e., the more uniform the near-field profile, the smoother the target irradiation. Phase-correction techniques can be considered. In contrast, with a random phase plate, highly modulated speckle would be produced even for a plane-wave, near-field beam. Of course, if the near-field profile is perfectly smooth, then a phase plate would not be necessary for uniform target irradiation, providing that the beam was properly apodized to prevent Fresnel ringing. However, there are situations where it is advantageous to use a phase plate, such as for combining the foot pulse and main pulse on the OMEGA Upgrade laser.

The effects of phase aberrations on a ZCM can be reduced using either of the beam-smoothing techniques, induced spatial incoherence (ISI)[3] or smoothing by spectral dispersion (SSD).[4] To employ ISI, the phase plate would be divided into many (N) smaller ZCM's. The time-averaged interference among different ZCM's would be removed by introducing time delays among them, in increments of at least one laser coherence time. Any remaining interference would be the result of phase aberrations across the individual ZCM's. If the aberrations are of long spatial wavelengths across the beam, then the phase variation across each ZCM will be relatively small for moderate values of N. If these phase variations across each ZCM are all different, then the rms far-field fluctuation, for the superposition of all N ZCM's, will be reduced by $1/\sqrt{N}$, compared to the single ZCM result.

SSD can be used with a ZCM in exactly the same way it has been used with a random phase plate. Since SSD imposes a variation of "instantaneous" frequency (i.e., time-dependent phase) across the beam, the delicate balance of phase required for a ZCM is not satisfied instantaneously. However, when the far-field intensity is averaged over an integral number of modulation times (for sinusoidal phase modulation), then the ZCM phase balance is restored, as is true for the asymptotic time-averaged result. The effect of SSD is shown in Fig. 54.5, which shows the asymptotic result for (a) a random phase plate, (b) a 32 × 32 ZCM with the measured OMEGA phase error,[7] and (c) a ZCM with the OMEGA phase error reduced by 80%. Figure 54.5(b) used the measured phase variation from the central 20% of the OMEGA beam radius to estimate the phase error that might occur for the foot pulse of the OMEGA Upgrade. (The foot pulse in the original design for the Upgrade occupied a slightly larger percentage of the beam aperture; the advantages of using a smaller size will be discussed.) In Fig. 54.5(c), this phase error was reduced by 80% to examine the effect of phase correction that might be possible for the static part of the foot-pulse aberration. In the limit of zero phase error, the time-averaged, far-field beam with SSD is perfectly smooth.

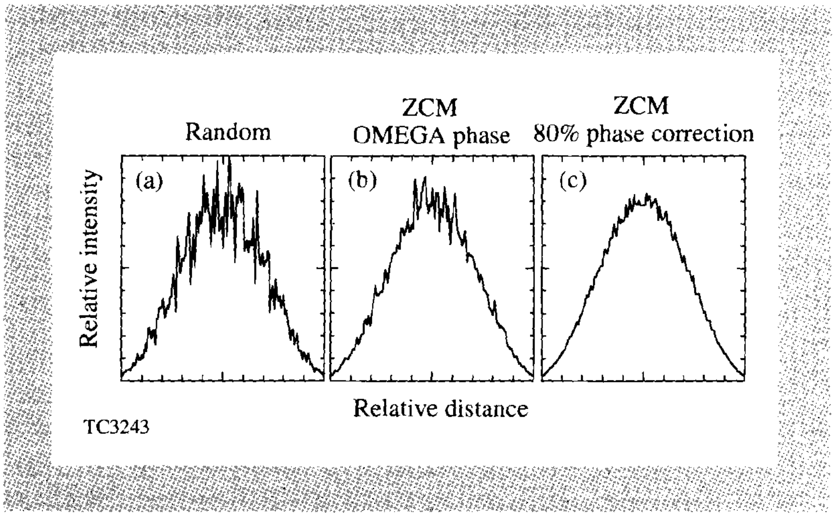

Fig. 54.5
The result of SSD (with one-dimensional dispersion) on the far-field intensity profiles for (a) a random phase plate with a polarization rotator; (b) a ZCM with the measured OMEGA phase error; and (c) same as (b) but with the phase error reduced by 80%. (SSD bandwidth = 10 Å, frequency = 30 GHz, dispersion = 300 μrad.)

Other Instantaneous Smoothing Techniques

We discuss two additional techniques for instantaneously eliminating far-field intensity fluctuations that can arise from interference among phase-plate elements. These techniques are limited to only a selected range of spatial frequencies, unlike the ZCM, which eliminates all spatial wavelengths of nonuniformity. However, these techniques are not sensitive to phase aberrations or other near-field imperfections.

1. Beam-Size Effects

The first of these techniques is relatively trivial but worth taking into consideration when designing a laser system. In most cases, the size of the laser beam is predetermined by energy, damage-threshold, and cost considerations. For those cases, the discussion in this subsection is not relevant. However, if the laser design offers some flexibility with regard to beam size, such as the foot pulse of the OMEGA Upgrade laser, then the following comments would apply.

The smallest possible beam size should be used for those applications that would benefit from elimination of irradiation nonuniformities with very short spatial wavelengths. Short-wavelength structure is produced from interference between phase-plate elements that are far apart. For a small beam, these distant phase-plate elements simply do not exist, and the resultant nonuniformity is limited to the longer wavelengths. For laser-fusion applications, this would mean complete elimination of the fastest-growing modes of the Rayleigh-Taylor hydrodynamic instability driven by laser nonuniformities.

There is considerable flexibility in choosing the size of the foot pulse for the OMEGA Upgrade laser, as the division of the pulse into low-intensity and high-intensity portions is somewhat arbitrary. There are two main constraints from a laser point of view: (1) The foot pulse must be large enough to adequately pass through the spatial filter pinholes. (2) Enough low-intensity light must have been removed from the main pulse that the efficiency for frequency tripling remains relatively high. From a laser-target point of view, the main constraint is that the foot pulse must contain enough energy to create a sufficiently large plasma atmosphere that the short-wavelength structure will be smoothed at the onset of irradiation from the main pulse. These considerations can be met if the foot pulse is several times smaller than in the original OMEGA Upgrade design.

For a ZCM, there is an additional advantage to using the smallest possible foot pulse on the OMEGA Upgrade. The phase variation is often the most uniform near the very center of the aperture. Using only this region minimizes intensity fluctuations produced in the far field of the ZCM. For these reasons, we have assumed a relatively small foot pulse in the examples here.

2. Controlled Amplitude Modulation

A second technique for eliminating interference structure among phase-plate elements is to impose controlled amplitude modulation throughout the pulse, together with time delays across the phase plate, so that only selected elements are illuminated at any one time. Then, of course, there cannot be any interference among phase-plate elements that are not simultaneously illuminated.

A schematic of this concept is illustrated in Fig. 54.6. Regularly spaced amplitude modulation is imposed upon the beam such that, in this example, the pulse is "on" 25% of the time and "off" the remaining 75% of the time. Such modulation could be imposed by spectral pulse-shaping techniques discussed in Ref. 8. At the phase plate, a time delay is introduced across different sections of the beam. In this example, four time-delay steps would be used, with step increments of 1/4 the cycle time between amplitude peaks. Only two of the steps are displayed in the figure. The result is that when one quadrant is being illuminated with a pulse peak, the other quadrants are "off." This completely eliminates interference among phase-plate elements from different quadrants and, consequently, further reduces the short-wavelength nonuniformity produced from interference among distant elements.

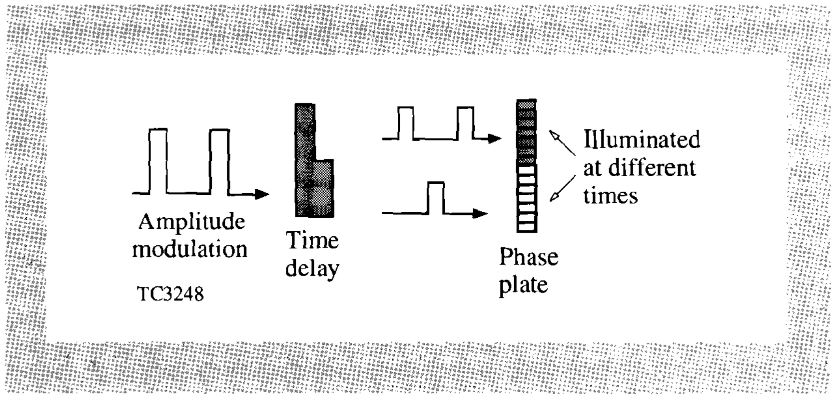

Fig. 54.6
Controlled amplitude modulation. Regularly spaced amplitude modulation is imposed upon the beam early in the laser chain. At the phase plate, time-delay steps are used to segment the beam so that only one section of the phase plate is illuminated with the intensity peak at any time, thereby eliminating all interference among different sections. In the figure, the shortest possible wavelength structure has been eliminated by preventing interference among the most-distant phase-plate elements.

Note that even though the pulse is "off" 75% of the time, the target is still continuously illuminated. At any time during the pulse, light is passing through one of the phase-plate quadrants. Since every phase-plate element completely irradiates the target, continuous uniform target illumination is obtained. Clearly, the intensity in each amplitude spike would have to be four times larger than the average intensity required to drive the target. This is ideal for the foot pulse, as the increased intensity would enhance its frequency-tripling efficiency.

Controlled amplitude modulation can be combined with ZCM's by choosing each of the phase-plate quadrants to be a separate ZCM. In the limit of perfect near-field conditions, each quadrant would produce a smooth intensity profile on target.

Combining Several Techniques

An example of combining all the beam uniformity techniques previously discussed is shown in Fig. 54.7. A small beam with a 32 × 32 phase plate is used. The beam is segmented into four parts, each with a different frequency. With this

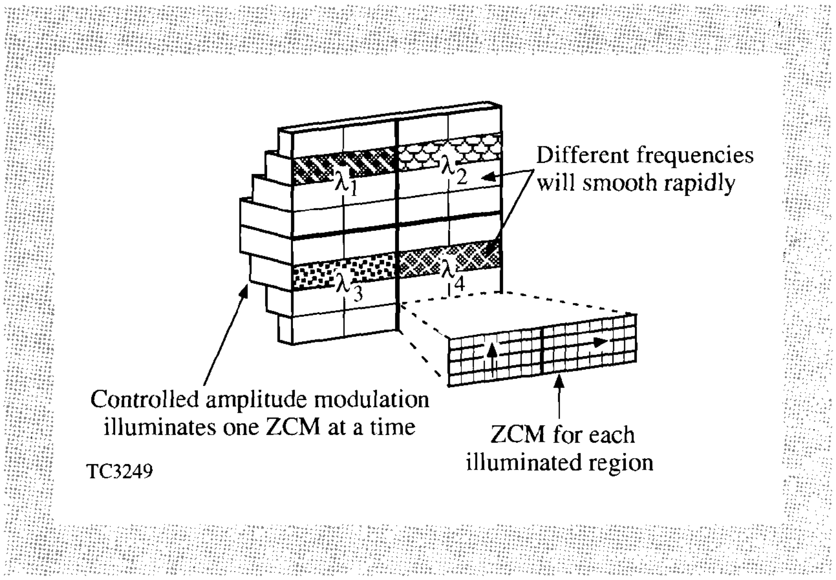

Fig. 54.7
One possible configuration for combining different beam-uniformity techniques. These include ZCM, controlled amplitude modulation, and SSD.

form of SSD using spatially separated frequencies, as opposed to phase-modulated bandwidth, all interference among the different beam segments will be completely smoothed in time, without leaving any residual nonuniformity. Each beam frequency irradiates a 16×16 quadrant of phase-plate elements. Each of these quadrants is further subdivided into four sections with the time-delay steps used for implementation of controlled amplitude modulation. Each of these sections is chosen to be a separate 4×16 ZCM. Since each ZCM is, in fact, divided into two noninterfering portions by means of a polarization rotation, the full phase plate has now been separated into 32 incoherent, or totally noninterfering, sections, each of dimension 4×8.

The interference structure produced by each 4×8 section is cancelled by its ZCM complement for perfect near-field conditions. For significant near-field fluctuations, the asymptotic nonuniformity is similar to the incoherent superposition of 32 intensity patterns from different 4×8 random phase plates. The shortest spatial wavelength of any asymptotic nonuniformity structure is determined by the size of the 4×8 subsection of the phase plate. Instantaneously, however, there is a shorter-wavelength structure produced by the interference among rays of different frequency from more-distant phase-plate elements. But this interference will smooth to zero as $1/(\Delta\nu T)$, where $\Delta\nu$ is the frequency difference and T is the averaging time.

We have calculated the nonuniformity that might be expected using these combined techniques on the foot pulse of the OMEGA Upgrade laser. The inner 20% of the measured OMEGA phase aberration was used without assuming any phase correction. The IR beam was assumed to be segmented into four parts, each with a different frequency. The frequencies were in increments of 150 MHz (5 Å), which was tripled upon frequency conversion. Controlled amplitude modulation was imposed with a cycle time of 20 ps. The resulting nonuniformity was calculated as the rms variation on a spherical target for 60 overlapping beams.

The time-averaged, rms intensity variation is plotted as a function of averaging time in Fig. 54.8, for three different uniformity techniques, each using a 32 × 32 phase plate with a polarization rotator. The curve marked "current" is with the current form of SSD using 9-GHz sinusoidal phase modulation and 3 Å of bandwidth spectrally dispersed in one dimension. The curve marked "near term" shows the improvement obtained with two-dimensional SSD using 30- to 40-GHz modulation frequencies and 7-Å bandwidth dispersed in two perpendicular directions. Finally, the combination of techniques discussed in this article (using ZCM's, controlled amplitude modulation, and pure-frequency SSD) is shown as the curve marked "future." This curve indicates that rms values below ~1% can be achieved with smoothing times of the order of 10 ps–15 ps, using these combined techniques. This level of uniformity and smoothing time is consistent with currently accepted requirements for startup conditions. It should be emphasized that these calculations have not assumed any additional smoothing by thermal conduction within a plasma atmosphere. The laser irradiation was mapped directly onto the target surface to model startup conditions.

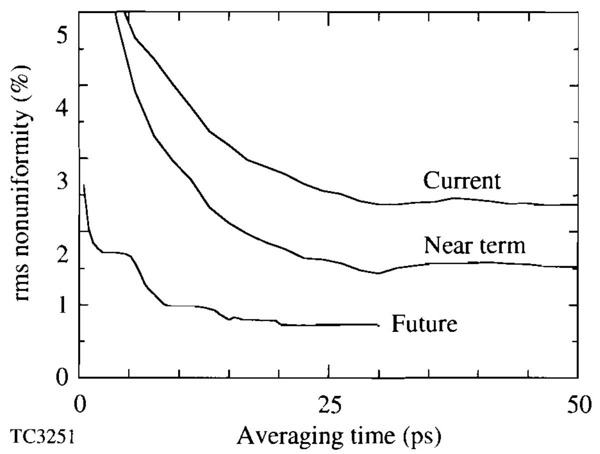

Fig. 54.8
The rms irradiation nonuniformity for 60-beam overlap on a spherical target. (a) current: one-dimensional SSD; (b) near term: two-dimensional SSD; (c) future: combination of ZCM, controlled amplitude modulation, and pure-frequency SSD shown in Fig. 54.7. All configurations used a polarization rotator and the measured OMEGA phase error (without phase correction). No thermal smoothing in a plasma atmosphere was assumed.

A treatment of the startup problem must address not only the magnitude of the irradiation nonuniformity, but also its spatial wavelength. A wavelength decomposition of the asymptotic nonuniformity for the "near-term" and "future" results of Fig. 54.8 is shown in Fig. 54.9, in terms of spherical harmonic mode numbers. The "future" uniformity techniques have essentially eliminated all short-wavelength structure corresponding to modes greater than ~30. These modes are considered the most dangerous for seeding the Rayleigh-Taylor hydrodynamic instability, as they grow the fastest.

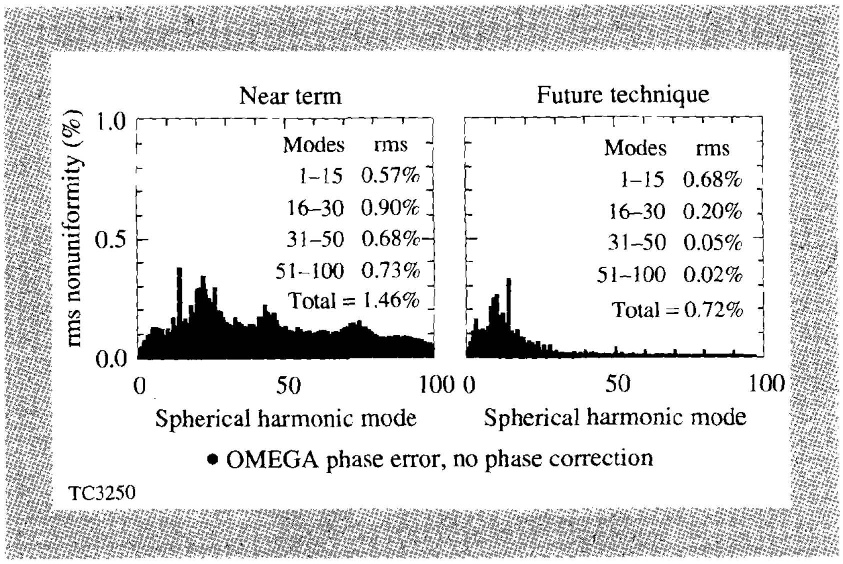

Fig. 54.9
A spherical harmonic decomposition of the asymptotic nonuniformity for the "near-term" and "future" results of Fig. 54.8. Note how the future technique has effectively eliminated all short-wavelength nonuniformity. All configurations used a polarization rotator and the measured OMEGA phase error (without phase correction). No thermal smoothing in a plasma atmosphere was assumed.

Discussion

Several new techniques have been presented here for obtaining the high levels of uniformity required at the onset of laser irradiation. Undoubtedly, new variations of these techniques, as well as entirely new concepts, will be developed over the next few years, adding increased flexibility for achieving the required levels of irradiation uniformity. The methods for implementing and combining these techniques will depend on details of the individual laser system. The greatest flexibility is achieved when the low-energy, early-time portion of the pulse (foot pulse) is physically separated from the main pulse, as in the design for the OMEGA Upgrade laser. The best uniformity techniques might be wasteful of energy and inappropriate for the main pulse, but they could be implemented on the foot pulse where high uniformity is most crucial.

All of the new uniformity techniques discussed here would require some developmental work before they could be implemented on a high-power laser. For a ZCM, the technique for distributing the phases according to a specified pattern is current technology, but the required polarization rotation across half the phase plate has not yet been demonstrated. To date, a polarization rotator in the form of a wedge has been developed, where the polarization changes continuously across the phase plate. The extension to a single step should be straightforward. The technique for generating controlled amplitude modulation across the pulse, with a cycle time of $\lesssim$25 ps, has not yet been examined; however, it should be only a small extension of the spectral pulse-shaping techniques currently under investigation. (An array of high-optical-quality, time-delay steps properly registered with the phase plate would also have to be developed.) Finally, implementation of pure-frequency SSD would include developmental work for the following: (1) generating the discrete-frequency beams, (2) co-propagating the beams, and (3) frequency tripling. For example, when different frequencies were used in the calculations, they were spatially separated so that frequency tripling could be accomplished by means of optical wedges that will deflect each component through the tripling crystals at the optimal angle for that frequency. After the crystals, a second set of wedges would recollimate the beams.

Techniques such as these will be developed and implemented to meet the uniformity needs in upcoming experiments.

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