CONF-9505264--23

UCRL-JC-121195
PREPRINT

Illumination Uniformity Requirements for Direct Drive Inertial Confinement Fusion

J. E. Rothenberg
D. Eimerl
M. H. Key
S. V. Weber

This paper was prepared for submittal to the
1st Annual International Conference on Solid-State
Lasers for Application to Inertial Confinement Fusion
Monterey, California
May 30 - June 2, 1995

July 11, 1995

Lawrence Livermore National Laboratory

DISCLAIMER

Illumination Uniformity Requirements for Direct Drive Inertial Confinement Fusion

Joshua E. Rothenberg, David Eimerl, Michael H. Key†, and Stephen V. Weber

Lawrence Livermore National Laboratory, L-493
P. O. Box 808, Livermore, CA 94501
Telephone: (510) 423-8613 FAX: (510) 422-1930

ABSTRACT

The requirements for laser uniformity are discussed in terms of the ℓ-mode spectrum. It is shown that the choice of smoothing methods can significantly alter this spectrum and that this choice should be made in the context of the target physics. Although two dimensional smoothing by spectral dispersion yields a high quality near field beam profile, it results in poor smoothing for low spatial frequency. The partially coherent light method (fiber smoothing) leads to superior smoothing a low spatial frequencies, but has very poor near field beam quality. As a result, it may be desirable to use partially coherent light during the driver pulse foot (at low intensity and when minimizing the laser imprint is critical) and smoothing by spectral dispersion during the main pulse.

Keywords: Beam smoothing, smoothing by spectral dispersion, partially coherent light, induced spatial incoherence, inertial confinement fusion, direct drive.

1. INTRODUCTION

The laser driver requirements for the successful implementation of direct drive inertial confinement fusion (ICF) are significantly different from those for indirect drive. Direct drive requires a highly uniform illumination pattern on the target in order to minimize imprinted perturbations which are then greatly amplified by Rayleigh-Taylor (RT) growth. The various approaches[1-4] to this uniformity requirement all make use of target illumination with a time varying speckle pattern. The imprint of the high spatial frequencies from speckle on the target is ameliorated by the averaging of multiple uncorrelated speckle patterns over some effective integration time (governed by target physics and generally agreed to less than 1 nsec). The requirement on laser uniformity to achieve target ignition is then thought to be roughly stated in terms of requiring the total normalized variance of the time integrated intensity σ to be less than ~1%. However, given the complicated nature of the target physics, it is clear that a more detailed requirement is necessary.

2. TARGET PHYSICS OF DIRECT DRIVE ICF

The implosion process in direct drive ICF can be separated into a number of distinct phases, and although this tends to be an oversimplification, it is a useful framework from which to understand the uniformity requirements. The first phase is referred to as the imprint phase, where a relatively low foot intensity forms a plasma and laser nonuniformities transfer to (imprint on) the target surface. This process is spatial frequency dependent, and thus the surface RMS nonuniformity can be expressed as

$$\sigma_{imprint}(\ell) = \sigma_{laser}(\ell) \cdot \eta_{imprint}(\ell) \quad , \tag{1}$$

where $\sigma_{laser}(\ell)$ is the normalized laser variance, and $\eta_{imprint}(\ell)$ is the imprint efficiency. An example of a calculated imprint efficiency curve[5] is shown in Fig. 1, where it has been assumed that the target radius is $r_0 = 1.7$ mm, and thus the surface ripple wave number is related to ℓ-mode by $k = \ell / r_0$. The decrease in imprint efficiency at large spatial frequency seen in Fig. 1 is primarily a result of thermal diffusive smoothing of absorbed laser energy in the plasma surrounding the target.

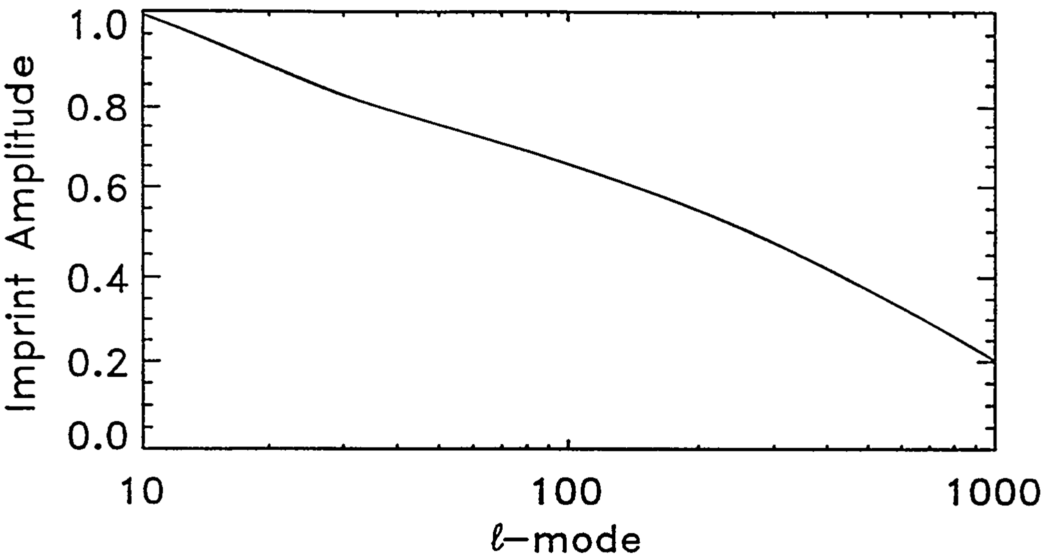

Figure 1: Spectral dependence of the laser imprint amplitude efficiency $\eta(\ell)$ (after Ref. 5).

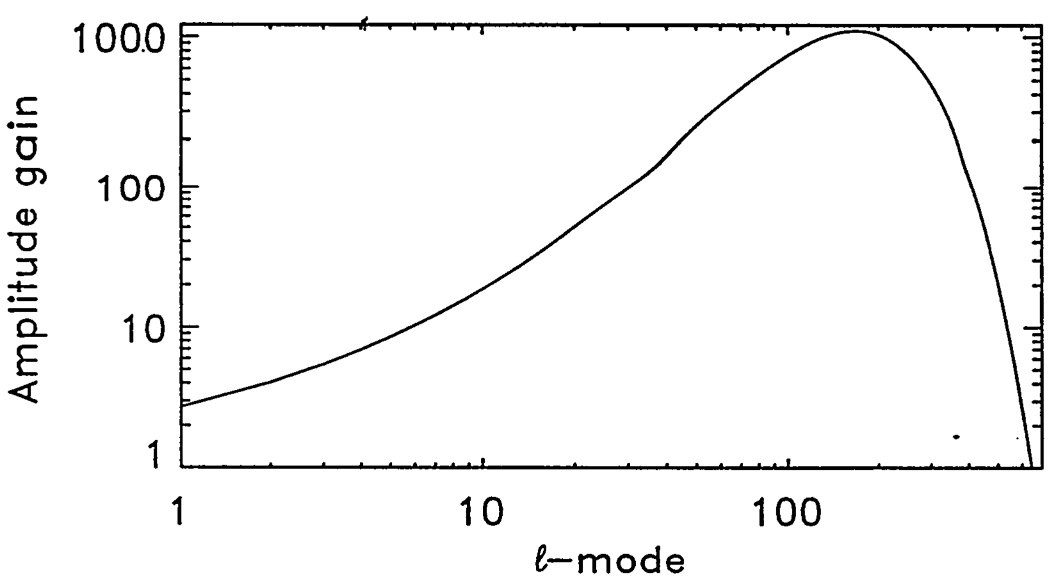

Figure 2: RT amplitude gain $\exp[\gamma(\ell)t]$ based on the modified Takabe formula for $\gamma(\ell)$ (Eq. 2), with the parameters given in the text.

As the laser intensity increases, the acceleration of the target shell becomes significant and the surface imprint ripples are amplified by RT gain. Although the amplification process is complicated by additional secular growth (linear and quadratic in time) as well as nonlinear saturation effects at large ripple amplitude, it is still useful to consider a basic estimate of the linear RT gain. A simple example of an RT gain estimate is shown in Fig. 2, which is based on the modified Takabe formula for the growth rate[6]

$$\gamma(\ell) \cong 0.9\sqrt{ka/(1+kL)} - 3kv_a \ . \qquad (2)$$

A simple 1D model at relevant laser plasma conditions yields values of the acceleration a=9·10[15] cm[2]/s, gradient scale $L = 1\ \mu m$, ablation velocity v_a=4·10[5] cm/s, and growth time t=5.0 ns. The amplified surface amplitude can now be written in terms of the ℓ-mode dependent imprint amplitude

$$\sigma_{RT}(\ell) = \sigma_{imprint}(\ell)\cdot \exp[\gamma(\ell)t] = \sigma_{laser}(\ell)\cdot \eta_{imprint}(\ell)\cdot \exp[\gamma(\ell)t] \ . \qquad (3)$$

Thus, given the spectrum of laser nonuniformity $\sigma_{laser}(\ell)$, one can estimate the peak amplified distortion of the accelerating target shell. It is noteworthy that the peak RT gain occurs for $\ell = 100-300$, and therefore the spatial frequencies in this range are the most critical to beam smoothing.

3. ILLUMINATION UNIFORMITY REQUIREMENTS AND BEAM SMOOTHING

One constraint on illumination uniformity is the requirement that the imploding shell maintain integrity during acceleration. An estimate may be made by requiring the aggregate surface deformation to be less than a significant fraction of the compressed shell thickness. Therefore, given the exponential RT gain, it is apparent that minimizing the imprint amplitude is essential in maintaining the shell integrity during acceleration. Optimized beam smoothing during the imprint phase is the key ingredient in accomplishing this.

The second constraint on illumination uniformity appears in the final stage of implosion. In this last stage the shell acceleration reverses and surface perturbations feed through to the inside surface as evanescent waves, which most strongly passes ℓ-modes less than ~20. There is further RT gain of low ℓ-modes during deceleration preceding the ignition of the hot core. The second uniformity constraint follows from requiring that the symmetry of the core be maintained so that mixing of cool fuel into the hot core is not significant.

From the above considerations one obtains two requirements on the laser uniformity, one on low ℓ-modes (beam symmetry) and the other on higher ℓ-modes (beam smoothing). Based on target simulations,[5] the aggregate RMS upper bounds for fluence uniformity (with an integration time ≤ 1 nsec) have been estimated to be 1% for $\ell \leq 20$ and 0.5-1% for $\ell > 20$. For the low spherical modes, the illumination nonuniformity is primarily determined by the effects of beam symmetry, profile, and overlap. The variance of fluence in these low ℓ-modes is very sensitive to the relative placement of the beams and their individual profile. For 48 beam clusters planned for the National Ignition Facility (NIF), it has been shown that by moving 24 clusters away from the locations ideal for indirect drive, uniformity below 1% is possible with suitable choice of the individual beam profile (~$\cos^{1.125}\theta$, where θ is the angular deviation from beam center measured from the target center).[7]

The high ℓ-mode uniformity is entirely determined by smoothing of the speckle. Given the finite integration time imposed by target physics, the integrated intensity variance produced by any smoothing method will ultimately be limited by the available laser bandwidth. For an integration time t and full extent of bandwidth $\Delta\nu$ one finds that total normalized variance is limited by $\sigma \geq 1/\sqrt{t\Delta\nu}$. In the NIF the anticipated bandwidth during the imprint phase (i.e. in the driver pulse foot, where intensity is greatly reduced) will be 0.5 - 1.0 Thz per beam at 3ω, and each of 48 beam clusters comprises four beams of frequencies separated (at 3ω) by 1-2 Thz. The total effective bandwidth will then be 2 - 4 Thz. For a bandwidth of 2 Thz, the above relation then yields a single cluster smoothing limit of no better than ~2.2% in an integration time of 1 ns. In addition, the overlap of illumination from the 48 clusters and two polarizations leads to an additional improvement of ~5 for an overall variance limit of ~0.44%. This last factor of improvement assumes that the spatial frequencies coherently produced by separate cluster overlap, corresponding to $\ell \sim 10000$, are not relevant to target performance. I.e., they imprint poorly (Fig. 1) and are well out of the relevant range for RT growth (e.g., as seen in Fig 2). Thus, one sees that the bandwidth limited smoothness is consistent with the above estimated requirements for uniformity. Based on the above assumptions, the fluence variance can reach the 1% level in an integration time of ~200 psec.

Recent calculations have shown that smoothing approaching the bandwidth limit is attained during the first nanosecond of integration time by using two dimensional smoothing by spectral dispersion (2D SSD).[8] In 2D SSD gratings disperse the source bandwidth in the far field (i.e. on the target), but the near field intensity remains essentially unmodulated. In an alternative smoothing method one images a changing speckle pattern (partially coherent light or PCL) through the laser and onto the target. A convenient implementation of PCL utilizes a long multi-mode fiber to generate spatial incoherence on a broad band source laser (Fig 3).[3]

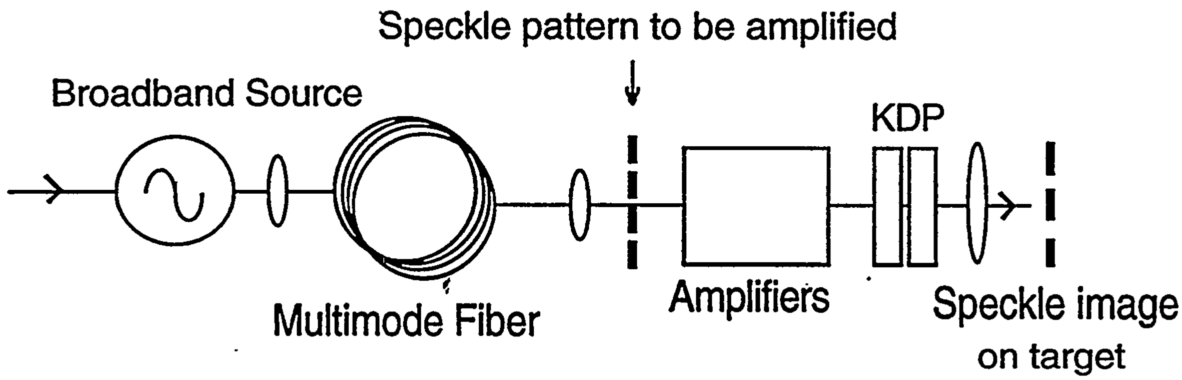

Figure 3: Fiber smoothing technique for generating PCL.

To determine the optimal smoothing method for direct drive, one must compare the target response to the spatial spectrum of the illumination nonuniformities over the relevant integration time. Whereas SSD has the advantage of preserving near field beam quality, the smoothing of low ℓ-modes is inferior to that of the PCL smoothing method. Figure 4 shows a comparison of the spatial spectra produced by the SSD and PCL smoothing methods at three integration times, where the NIF geometry of a 7 m focal length and 40 cm single beam aperture has been assumed.

As can be seen in Fig. 4 the PCL method results in smaller nonuniformities than does 2D SSD for ℓ-modes less than ~ 400, and the improvement using PCL is quite large for ℓ-modes less than ~50. However, the total RMS content of these low ℓ-modes is very small. Even with smoothing by 2D SSD, the total nonuniformity of modes with $\ell < 20$ is (for 192 beams and two polarizations) only ~0.2%, which is much less than the ~1% nonuniformity from beam pointing symmetry. The comparison between these two methods is thus most important in the region of larger ℓ-mode and peak RT growth (ℓ ~ 50-400). A comparison of the aggregate variance in different ℓ-mode bands is shown in Table 1.

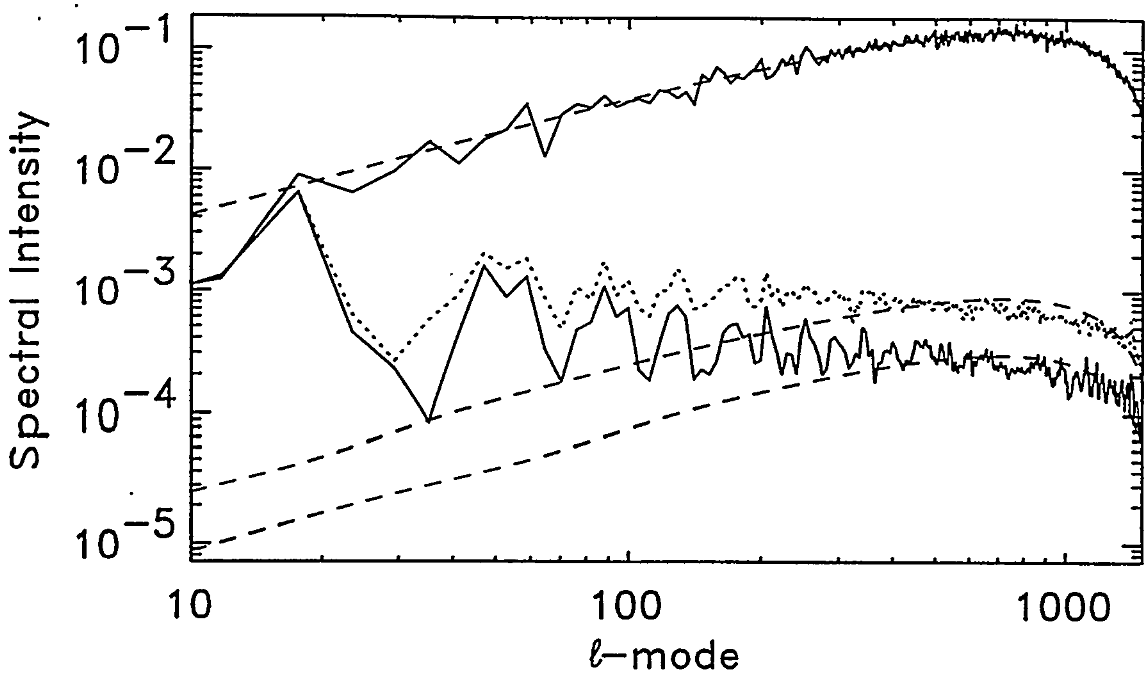

Figure 4: Calculated ℓ-mode power spectrum of laser nonuniformity for PCL (dashed curves) and 2D SSD (solid and dotted curves) for integration times of (top to bottom) 0, 300, and 1000 psec. The 2D SSD calculation assumes 8.2 and 3.4 Ghz modulation frequencies and both methods assume an aggregate bandwidth of 500 Ghz.

Table 1

Aggregate normalized variance of smoothed speckle as a function of ℓ-mode for 2D SSD and PCL smoothing methods. 500 Ghz bandwidth, 1 ns integration time, 192 beams and 2 polarizations are assumed.

ℓ-mode	1 - 20	20 - 50	50 - 200	200-400	400 -1500
SSD	0.21%	0.11%	0.22%	0.21%	0.40%
PCL	0.011%	0.024%	0.10%	0.16%	0.41%

From Table 1 one sees that although PCL yields much better smoothing at low ℓ-mode, the bulk of the aggregate variance occurs at large ℓ-mode (simply owing to the larger number of total modes), and in this region SSD and PCL achieve very comparable levels of smoothness. Since ultimately one is only concerned with target performance, a more meaningful comparison includes the effect of the ℓ-mode dependent imprint efficiency and RT gain in comparing the total amplified surface perturbation. As a simple example of such a comparison, the imprint and gain from Figs. 1 and 2 are assumed, and the laser spatial spectrum is taken from Fig. 4 for both 2D SSD and PCL after a 1 nsec integration time. These spectra are substituted into Eq. (3) to obtain the amplified imprint spectra for both PCL and 2D SSD (Fig. 5). Figure 5 shows that the peak modes in the range ℓ ~ 100 -300 are reduced in size by the PCL method compared with that obtained with 2D SSD. Integration of this result over spatial frequency yields the result that the aggregate RMS of the amplified surface perturbation using the PCL method is less by a factor of 1.8 than that of 2D SSD. Although this result gives an indication that the

PCL method may have some advantage over 2D SSD, the target physics has been greatly simplified here; variation in the target design may significantly alter the RT gain spectra, and in all cases a rigorous analysis of the target response is required to determine which smoothing method is superior. In particular, it is clear from examining Fig. 5 that should the RT gain curve peak at ℓ-mode larger than that shown in Fig. 2, the aggregate smoothness advantage found for the PCL method will decrease.

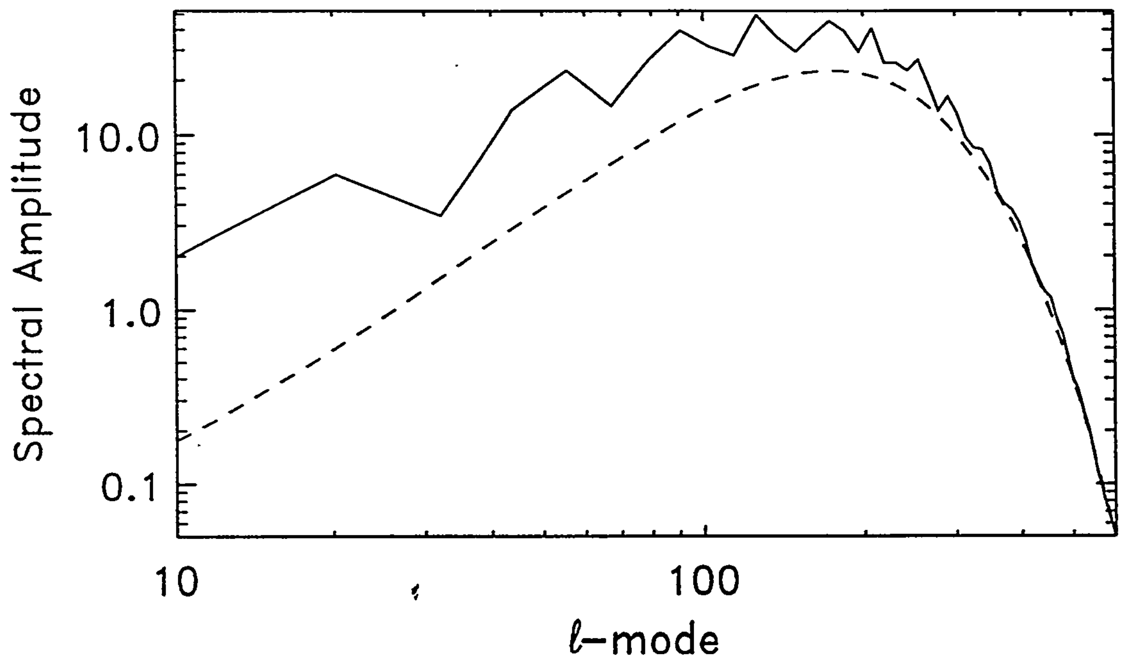

Figure 5. Spatial amplitude spectrum of imprint perturbations amplified by RT gain assuming 2D SSD (solid curve) and PCL (dashed curve) smoothing; integrated for 1 ns at 500 Ghz bandwidth. The imprint efficiency and RT gain are taken from Figs. 1 and 2.

4. OPTIMIZING SMOOTHING DURING THE LOW INTENSITY PULSE FOOT

A major disadvantage of the PCL method is the poor near field beam quality, which limits the peak intensity of the laser.[9] Should the additional smoothing of low ℓ-modes by using PCL be desirable, it is possible to use PCL during the driver pulse foot (at low intensity, where the near field beam quality within the laser is of reduced significance) when reducing the imprint is most critical, and switch (electro-optically for instance) to SSD before the main pulse. A particularly simple technique of switching from PCL during the pulse foot to SSD during the main pulse is to use an integrated optic multiplexer to control the routing between two fiber optic channels, one single and one multi-mode, and to recombine after propagation through the fiber channels (Fig. 6). Given this dual smoothing approach, one must optimize the phase plate for both smoothing methods and ensure that the proper beam size on target is maintained.

One can also utilize this type of switching concept to improve the smoothing rate of SSD during the imprint phase by switching the bandwidth of the phase modulation between the main and foot pulse. During the pulse foot, when smoothing rate is critical and conversion efficiency is less so, the bandwidth and beam divergence are driven to a maximum, whereas, during the main pulse the converse applies and the bandwidth and divergence are reduced to ensure optimal laser performance and adequate conversion efficiency (in this case, the bandwidth and divergence reduction can be accomplished just by reducing the phase modulator driver power). An additional benefit of this approach would be the concomitant reduction in beam size (owing to the reduced laser divergence) during the main pulse, which could improve the driver energy coupling efficiency.

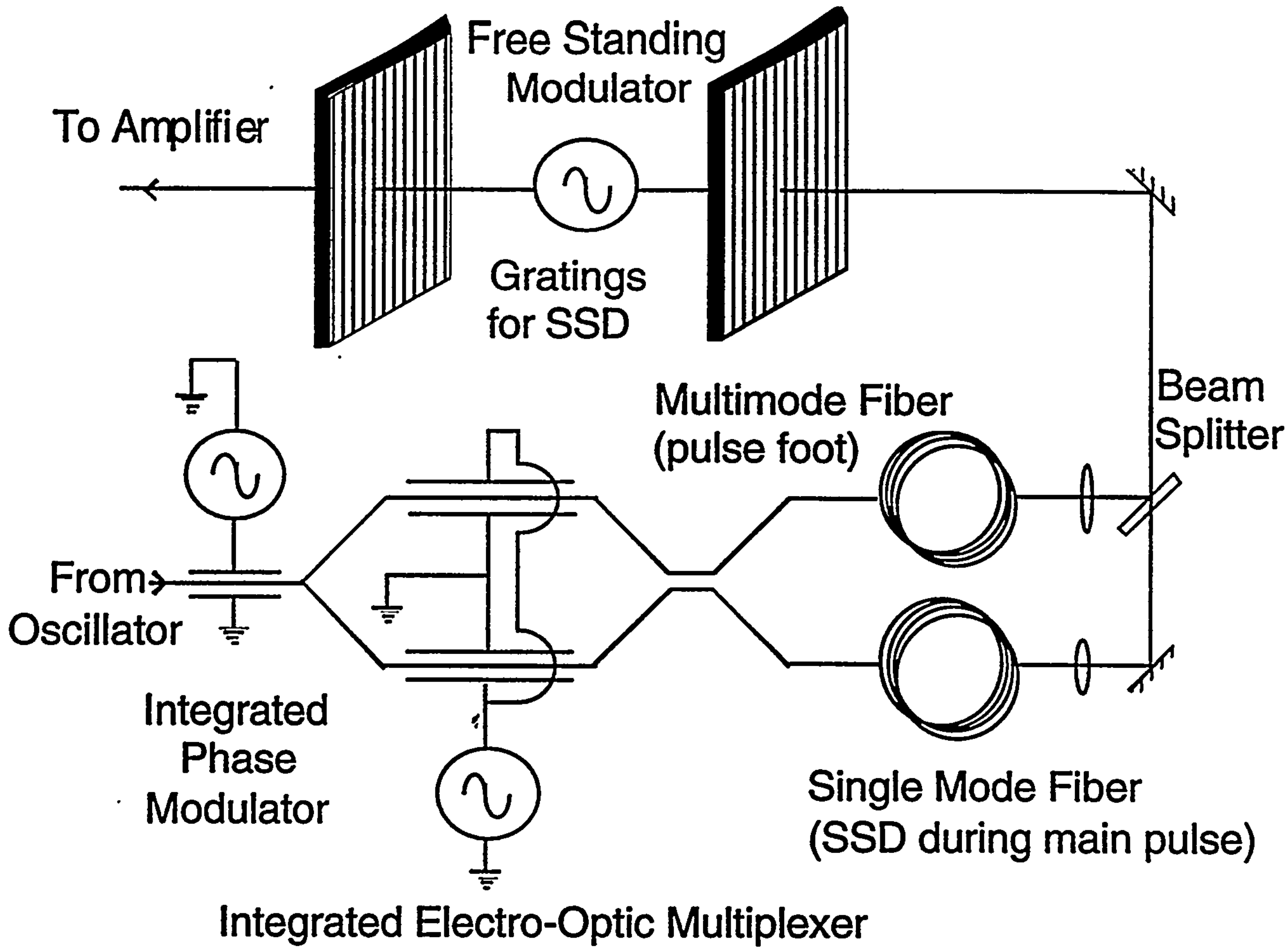

Figure 6: Integrated optic implementation which allows for switching from the PCL method to the clean near field of the SSD smoothing method between the foot and main pulse. An integrated phase modulator can provide bandwidth, and an electrooptic multiplexer can rapidly switch the pulse between a single mode (clean near field) and multimode (PCL) fiber channel. After recombination both channels undergo additional (1D or 2D) SSD to insure adequate smoothing during the main pulse.

5. CONCLUSIONS

The instability of surface perturbations leads to the conclusion that illumination uniformity is critical in direct drive target performance. The uniformity is determined by beam overlap and symmetry (for low ℓ-modes), and bandwidth and beam smoothing method (for high ℓ-modes). To optimize target performance, one must consider the spatial spectrum of the laser nonuniformities, and the resulting target response. In this regard, the PCL smoothing method may offer some advantage over 2D SSD. However, detailed target simulations are necessary to properly perform this comparison. The disadvantage of poor near field beam quality of the PCL method may be overcome by using PCL only during the pulse foot and switching to the clean near field of SSD before the onset of the main pulse. Similarly, the bandwidth used with SSD may be maximized during the pulse foot to ensure optimal smoothing, and then reduced before the onset of the main pulse to insure proper laser performance and frequency conversion.

6. ACKNOWLEDGMENT

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

7. REFERENCES

1. R. H. Lehmberg and S. P. Obenschain, Optics Comm. **46**, pp. 27-31 (1983).

2. Y. Kato, K. Mima, N. Miyanaga, S. Arinaga, Y. Kitagawa, M. Naktsuka, and C. Yamanka, Phys. Rev. Lett. **53**, pp. 1057-1060 (1984).

3. D. Véron, H. Ayral, C. Gouedard, D. Husson, J. Lauriou, O. Martin, B. Meyer, M. Rostaing, and C. Sauteret, Optics Comm. **65**, pp. 42-45 (1988).

4. S. Skupsky, R. W. Short, T. Kessler, R. S. Craxton, S. Letzring, and J. M. Soures, J. Appl. Phys. **66**, pp. 3456-3462 (1989).

5. C. P. Verdon, unpublished

6. M. Tabak, D. H. Munro, and J. D. Lindl, Phys. Fluids B **2**, pp1007-1014 (1990).

7. D. Eimerl, paper T-12 in these proceedings.

8. J. E. Rothenberg, paper P-16 in these proceedings.

9. D. Véron, G. Theill, and C. Gouedard, Optics Comm. **97**, pp. 259-271 (1993).

---

† permanent address: Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11QX, United Kingdom