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NIF Optics Phase Gradient Specification

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SUBJECT: NIF Optics Phase Gradient Specification
(A summary of a briefing given 4/24/97 on this subject)

Summary

A root-mean-square (rms) phase gradient specification seems to allow a good connection between the NIF optics quality and focal spot requirements. Measurements on Beamlet optics individually, and as a chain, indicate they meet the assumptions necessary to use this specification, and that they have a typical rms phase gradient of $\sim 80 \text{ \AA/cm}$. This *may* be sufficient for NIF to meet the proposed Stockpile Stewardship Management Program (SSMP) requirements of 80% of a high-power beam within a 200-250 micron diameter spot. Uncertainties include, especially, the scale length of the optics phase noise, the ability of the adaptive optic to correct against pump-induced distortions and optics noise, and the possibility of finding mitigation techniques against whole-beam self-focusing (e.g. a pre-correction optic). Further work is needed in these areas to better determine the NIF specifications.

This memo is a written summary of a presentation on this topic given by W. Williams 24 April 1997 to NIF and LS&T personnel.

Introduction

The rms phase gradient and the Power Spectral Density (PSD) are currently proposed as primary specifications for NIF large optics. The former addresses phase features with long scale lengths (∞ to $\sim 3 \text{ cm}$), and the latter to smaller features (3 to 0 cm). The exact ranges and values for these specifications have not been fully determined at this point.

In this discussion we focus on the gradient specification only. The PSD specification covers high-frequency portions of the phase noise spectrum. In a well-designed system it will determine a relatively small fraction of the energy in the focal spot ($\sim 1 \%$), so is less important in terms of focal spot requirements. This specification will be critically important, however, to controlling other concerns, including pinhole blow-off and beam modulation,

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with related issues of optics damage. As such, the PSD specification is the topic of ongoing studies by Charles Orth. While separating these two phase frequency regimes into two specifications is convenient, more study is needed to determine the exact relationships between the two.

RMS Gradients: A Ray Optics Approach (J. Downie)

The possibility of using an rms phase gradient specification for NIF was proposed by John Downie last year (see memos NIF-0000325, NIF-0000613, and NIF-00001385). For long-wavelength aberrations on the phase, the propagation distances in NIF are short enough (10-20 m out of relay) that these aberrations remain as phase, and do not convert to amplitude. Therefore, the long-wavelength portion of the phase field presented to the target is simply the sum of the various contributors to the beam phase as it passes through the chain. Further, as a starting point, we can assume that all optics add the same phase noise to the beam, as measured by the power in each spatial frequency band, but that the power in each band has random phase from optic to optic, so they add incoherently. Thus, we can root-sum-square (rss) add the noise from each optic to get the total noise on the beam at the end of the chain, without doing any propagation calculations.

Considering the beam which presents itself to the final focus lens, from a ray optics treatment, the directions of the rays in the beam, and the resulting focal spot distribution, are set by the gradient distribution of the phase front across the aperture. (Rays travel normal to the phase front.) Further, if we assume that this gradient distribution is Gaussian then a knowledge of the rms gradient alone is sufficient to describe the entire spot distribution (a Gaussian being a 1-parameter function in shape). Within this framework, the phase front may have long scale lengths and large amplitudes, or short scale lengths and small amplitudes, and retain the same phase distribution, rms phase gradient, and focal spot. Neither the characteristic scale length of the phase noise nor its amplitude (peak-to-valley) is directly important to the focal spot, only the ratio of the two (in the sense that this defines the gradient). (Anticipating discussion below, however, one can visualize that the scale of the noise would impact how well the adaptive optic, with its fixed actuator spacing, will be able to correct the noise, and in that way, affect the focal spot.)

The assumption that the gradient distribution is Gaussian allows a direct tie between the rms gradient and the spot size. Numerical simulations (R. Sacks) suggest that the spot size depends only on the rms gradient for some non-Gaussian distributions also. Figure 1 shows the spot size as a function of the scale size (defined below, but sort of the characteristic scale size of the phase noise) for phase representations constructed using various spectral filters. (The phase is the inverse Fourier transform of the product of the indicated distribution and a uniformly distributed random number sequence.) One can see that, within a reasonable tolerance, the spot size is only a function of the rms gradient, and that different distributions have the same spot size, given the same rms gradient. The theoretical basis and limits behind this observation are still being considered. It does suggest, however, that the optics for NIF do not have to have strictly Gaussian gradient distributions for an rms specification to be relevant.

In these results the rms gradient is actually the rms gradient magnitude, or rms of $\sqrt{\nabla_x^2 + \nabla_y^2}$.

Phase Distributions on Measured Parts

Measured parts, however, do in fact seem to have reasonably Gaussian gradient distributions. Figure 2 shows the y-gradient distributions for a number of full-aperture parts. (CP BK7 is a slab of continuous-pour BK7.) Additionally, the gradient distribution for the passive (unpumped) transmission through the Beamlet chain is shown (courtesy P. Wegner). It, also, looks relatively Gaussian.

We can use these measurements to determine a typical rms gradient for real parts, either by looking at the parts one at a time, or by looking at the phase noise imparted on a beam from many parts, and statistically arguing the contribution from one average piece. Using this latter approach first, Figure 3 shows the phase on the unpumped ("rod shot") beam in Beamlet. Following Downie's assumption above that parts add incoherently, and given 15 four-passed elements, 10 two-passed elements, and 15 one-passed elements, we find the optic-average rms gradient is equal to the rms gradient for the whole chain, divided by $\sqrt{295}$. This gives an optic-average of $\sim 80 \text{ \AA/cm}$ for Beamlet.

Figure 4 shows this value, along with the rms gradients as measured on a number of individual parts. We see the rms gradient for individual laser slabs ranges from 40-80 $\text{\AA/cm}$, and is consistent with the value of 80 $\text{\AA/cm}$ derived from the whole chain. The continuous-pour BK7 sample has a substantially higher rms gradient of 130 $\text{\AA/cm}$. Laser slabs mounted on frames (bau files) have rms gradients from 40 to 100 $\text{\AA/cm}$. These data seem to suggest that an average rms gradient for these large-aperture transmission optics is 40-80 $\text{\AA/cm}$.

Also shown in this figure is information regarding the scale length of the aberrations on each part, and for the sum of optical aberrations through the Beamlet chain. These are seen to range from 1 to 8 cm. This scale length is defined in two ways. As used below in random Gaussian phase files for performance simulations, it has to do with the Gaussian function convolved with a random number sequence to make the random phase screen. Assuming Gaussian statistics, this scale length is also related to the auto-correlation function, however. Specifically, if one takes the auto-correlation function of the phase map of a part and fits a Gaussian to that function, the scale length is the $1/e$ radius of that Gaussian (in units of cm) divided by $\sqrt{2}$. This is the method by which the scale length for real parts, shown in Figure 4, is determined. It is a relatively abstract measure, and so can be confusing. To this point, however, we have not identified a metric which would be more intuitive while still being computationally as useful. For optics fabricators, Figure 4 is intended to provide at least a working definition of scale length, in that individual parts, whose processing and fabrication histories are known, can be correlated with their scale lengths.

Though not yet completely understood, it is of interest that the scale length for the phase front from the Beamlet chain is considerably larger than that of individual parts (4-5 vs 1-3 cm). We have proposed two possible reasons for this. First note that the mounted laser slabs (bau files) also have considerably larger scale lengths than the unmounted slabs (5-8 vs ~ 1 cm). This suggests that mounting may induce a long scale aberration in the part. With a simple numerical simulation, it can be shown that this could create the effect seen: an increase of the scale length, as measured with the auto-correlation technique discussed above, without substantially changing the rms gradient. Such a mounting distortion may make the statistics of the optic significantly non-Gaussian (with the small-scale noise riding on a long-scale mounting warp).

The other possible contributor to the increase in scale length concerns the assumption that noise sources from sequential optics in a chain add incoherently. It may actually be true that the longer scale features in the optics will add coherently so that these scale sizes will be accentuated in the beam after propagation through the whole chain, as compared with the scale sizes seen in one part. Whether one or both of these effects—mounting or long-wavelength coherence—is contributing to the shift in scale length from shorter for individual parts to longer for the whole chain, deserves significantly more investigation. The parts are specified in isolation, unmounted, whereas the adaptive optic corrects the aggregate beam from mounted parts.

NIF Specifications

It is convenient for conceptual and physics reasons to divide the NIF optics specifications into two categories — the rms gradient specification and the Power Spectral Density (PSD) specification. We do this by considering the focal spot to have two regions, the center core, and the tails. (See Figure 5 for an example.) The shape of the core directly affects our ability to meet the power/energy requirements of (especially) the SSMP missions for NIF (80% of the high-power beam inside a 200-250 micron diameter circle). The shape of this core is determined by the long-wavelength aberrations on the beam from several sources including optics quality, pump-induced distortions, whole-beam self-focusing, residual thermal gradients in the optics, thermal turbulence in the air, mounting distortions, and phase noise from the front end. The adaptive optic will correct these noise sources, to the extent possible. The rms gradient specification is intended to address the optics quality contribution to this core focal spot shape.

The tail of the focal spot is important for reasons other than directly meeting functional requirements, especially the need to control near-field beam modulation, which can cause damage spots on optics (including beam filamentation); and pinhole plasma blow-off, with subsequent possible pinhole closure and damage to the pinhole. This tail is mostly provided by the tails of the phase noise from the optics quality, and the physics of these effects are sufficiently subtle and complex that they cannot be treated with a ray optics approximation. Study in this area is ongoing and not discussed in this report. Sufficient work has been done, however, to indicate that the specifications for the tail should probably be in the form of a PSD curve, broken into some form. In general, we consider that probably less than 1% of the total phase noise on a given optic should be in this tail.

The spatial wavelength break between the two specifications is currently 3.3 cm, with the rms gradient specification applying to longer wavelengths and the PSD specification applying to shorter. This break is historical, and is connected to the spot size requirement for the ICF indirect drive mission of NIF. It also conveniently maps onto some Beamlet Schlieren data. More investigations need to be done to determine if this is still appropriate, especially considering the closeness of this to the scale sizes we find on measured optics (a few cm), and because it appears both specifications will be driven mostly by the SSMP mission for NIF.

Random Gaussian Phase Screens

To determine the appropriate values for the rms gradient specification, numerical simulations were done with PROP92 to compare a range of specification values against the functional requirement of 80% of the power within a 200-250 micron diameter circle. This requirement is for the 3w beam. Based on numerical and theoretical arguments, it can be shown that the 3w focal spot is very similar in size to what a 1w focal spot would be without a frequency converter at the 80% point. Because of this, we did simulations of the 1w beam only, comparing this to the 3w requirement.

To do simulations we need a random phase noise for optics which meets the requirement of a Gaussian gradient distribution. One such incarnation is a random Gaussian phase screen. This is generated by convolving a Gaussian function with a uniformly-distributed random number sequence, as shown in Figure 6. *This convolution provides the numerical definition of scale length, s_g .* With different random number sequences, unique phase screens can be created which have the same Gaussian statistics, but which add incoherently with each other. For simulations, enough such screens are created for all the optics in the main NIF chain, all with the same s_g and scaled to have the rms gradient. An example of one such screen, with a greatly exaggerated magnitude scale, is shown in Figure 6. Looking at the gray-scale image, one can see that s_g is sort of like the radius of the characteristic scale size in the phase. (As indicated above, however, it is more accurately described either by the convolution Gaussian, or by a Gaussian fit to the auto-correlation function.) Use of this approach to studying the rms gradient specification then allows two free parameters: the rms gradient and the scale size. These parameters are varied in the following results.

Modeling Assumptions

Modeling was done using PROP92. A description of this code and most of the detailed modeling assumptions are not given here. A few specific assumptions, however, are as follows:

- 1) Beamlet size beam: 1000 cm², 1 cm erf edge (~2 cm roll-off from top to bottom), on 256 x 256 grid.
- 2) NIF size beam: 1250 cm², 1.5 cm erf edge (~3 cm roll-off from top to bottom), on 256 x 256 grid.
- 3) 100 microrad half-angle pinholes in all filters.
- 4) Random Gaussian phase screens as described on all optics, covering a range of scale lengths from 2 to 8 cm, and rms gradients from 25 to 100 Å/cm (created on 128 x 128 grid).
- 5) PSD simulation files (covering 0-100 microrad) on all optics: There is some overlap in spectral power between the random Gaussian phase screens and the PSD files. This overlap is shown in Figure 7. Future simulations should have this overlap removed. It is assumed not to be a large effect, and makes these simulations conservative.

- 6) Beamlet pump-induced distortions: This is one file taken from a measurement by P. Wegner (B7012404), and includes the aggregate of all pump-induced distortions for the whole chain (see Figure 8). It was experimentally derived by generating an-unpumped beam, with as flat a phase as possible at the output of Beamlet. The amplifiers were then pumped, and the resulting phase measurement was used in calculations. It is an overestimate because the unpumped phase has not been subtracted out, due to an oversight in our use of the information. This "background" for the rod shot corrected as flat as possible, is on the order of 1 wave, peak to valley, or ~30% of the pumped measurement. Consequently, the pump-induced distortion used in calculations is probably too large, by as much as 30%. In addition, the vertical roll-off seen in the data has not been expected from modeling studies by M. Rotter, and is not clearly understood. A final uncertainty concerns the difference in pump pulses expected between Beamlet and NIF. Specifically, the NIF pump pulse is ~360 microsec and the Beamlet pulse is somewhat longer (400-500 microsec), and the reflector geometries are not the same. The pulse is actively deforming on the sub-100 microsec time scales, and the irradiation geometry is important to this deformation. Consequently, Beamlet is not a true representation of what NIF will see in pump-induced distortions. It is hoped that subsequent modeling, or results from AMPLAB will clarify these uncertainties.
- 7) PROP92 adaptive optic model: The numerical model used for the adaptive optic, developed by R. Sacks in PROP92, represents the actuators as having Gaussian influence functions (other shapes can be used). We set the actuator spacings as shown in Figure 9, with a 1/e influence function radius of 8 cm. The code adjusts all actuators to give an intensity-weighted minimum in the rms phase over the aperture. This model has not been compared in detail to the actual adaptive optic planned for NIF, nor does it use the Hartman sensor control algorithms intended for actual operation. It is anticipated that future modeling will include such improvements, with the use of codes developed by M. Henesian. In short, this model is considered a reasonable first-pass, but needs refinement.

Contributors to Spot Size

Before discussing results of modeling, it is useful to briefly discuss the various contributors to spot size. These are shown schematically in Figure 10. This modeling includes the contributions from optics quality, pump-induced distortions, and whole-beam self-focusing. (Whole-beam self-focusing refers to the phase gradient introduced on the edges of a high-power beam due to the non-linear index of refraction in optics through which the beam has passed. This phase gradient follows the intensity gradient of the apodization. It causes rays in the perimeter of the beam to be tilted inward, making a larger focal spot.) The modeling does not include several other potential contributors. SSD simply has not been modeled in NIF, at this point. Mounting and figuring errors may be substantial. To the extent these errors will be long-wavelength, however, they will only re-distribute energy in the focal spot, and not move it out of the 80% spot radius. Residual thermal aberrations result from incomplete cooling after previous shots, and can be large. In that context, this modeling represents "first shot of the day". Ditto for air turbulence.

These contributors must be corrected, to the extent possible, with the adaptive optic, to attain the 13-16 microrad half-angle (200-250 micron diameter spot) requirement for SSMP. These terms, the optics quality, pump-induced distortions, whole-beam self-focusing, and the

adaptive optic, all have large influence on the focal spot size. *Uncertainties in our modeling of the adaptive optic and pump-induced distortions make our predictions for the optics quality requirements correspondingly uncertain. Similarly, there is a reasonable possibility of introducing a static correction for the pump-induced distortion in the chain at some point (e.g. the phase plate or M2), but this potential has not been investigated, and no credit for doing so has been assumed in this modeling. If such proves feasible, it could substantially reduce the optics quality requirements.*

An example of a modeled focal spot with and without an adaptive optic can be seen in Figure 11. This is a case of a low-power beam with pump-induced distortions, having an s_g of 2 cm, and 50 Å/cm rms gradient optics. The leverage of the adaptive optic in reducing the spot size is clear as the 80% spot radius decreases from 28 to 16 microradians with the adaptive optic.

Modeling Results: Beamlet-sized Beam

Results are first shown with a Beamlet-sized beam (1000 cm²) in order to allow some comparison with data, and to suggest gains which may be accomplished by running a smaller beam in NIF. The primary effect is that the beam intrudes less into the steep-gradient edges of the pump-induced distortion regions of the slabs (see Figure 8, horizontal lineout).

These results are shown in Figure 12. A number of cases were run with different rms gradients on the optics, different scale lengths, and different assumptions regarding pump-induced distortions and whole-beam self-focusing. The data have been plotted as the 80% 1w spot radius vs the scale length of the optics aberrations. The four black curves represent a Beamlet rod shot: no pump-induced distortions or whole-beam self-focusing. The blue curves represent a low-power shot, where pump-induced distortions have been added. The green curves are high-power (4.2 GW/cm²) cases, including all effects. The red curves are non-physical and represent a high-power beam without pump-induced distortions. Because of uncertainty regarding the pump-induced distortion data, this represents the case of pump-induced distortion being totally corrected by an adaptive optic. Several conclusions are indicated:

- 1) Because the curves are flat, the assumption that spot size depends only on rms gradient and not the scale size of the noise, seems justified. (This was also shown in Figure 1.)
- 2) Measurements on a Beamlet rod shot give a spot size of ~15 microrad. If we assume a ~70 Å/cm optic-average finish for Beamlet, as suggested in Figure 4, this matches well the code predictions for 75 Å/cm, given by the heavy-dashed black curve.
- 3) Pump-induced distortions add significantly to the uncorrected spot size (10-15 microrad, the black and blue curves).
- 4) Whole-beam self-focusing adds little to the uncorrected spot size (2-5 microrad, the blue and green curves).
- 5) The high-power uncorrected spot is 30-35 microrad half-angle.

Similar studies were done with the adaptive optics turned on, shown in Figure 13. From these data it can be seen:

- 1) The adaptive optic substantially corrects the pump-induced distortions and optics aberrations, depending on scale length. Considering, for example, the black curves, one sees that at short scale lengths the adaptive optic (with its actuator spacing of ~ 6 cm) is unable to correct the optics aberrations, and there is a difference in focusability between the various rms gradient cases. With longer scale aberrations, however, the adaptive optic is better able to compensate, and given our model, which does not restrict actuator throw, can equally correct both small- and large-gradient cases for scale lengths of 8 cm. (The necessary actuator throws for these cases are not tabulated here, but are on the order of a few waves.) It is important to note that these results assume Gaussian statistics for the optics aberrations (Gaussian gradient distributions and Gaussian auto-correlation functions). Until other modeling is done, it is not known whether the adaptive optic will be able to achieve similar corrections for other distributions.
- 2) As discussed above, the pump-induced distortion model and/or the ability of the adaptive optic to correct it, are probably conservative. These are shown in comparing the blue and green curves with Beamlet data points shown on the axis. Assuming Beamlet optics have an average rms gradient of $70 \text{ \AA/cm}$, and a scale size of 1-3 cm (Figure 4), in both cases the model predicts a spot size 7-8 microrad larger than measured.
- 3) Whole-beam self-focusing adds significantly to the spot size (5-10 microrad, depending on scale size of the optics aberrations). This is seen by comparing the black and red curves.
- 4) With an adaptive optic perfectly correcting the pump-induced distortions (red curves), a rms gradient of $30\text{-}100 \text{ \AA/cm}$ is required, depending on the aberration scale size. Assuming a scale size of 1-2 cm, as found on measured parts, the lower bound of $30 \text{ \AA/cm}$ is needed. If the scale size is 6 cm or larger, the deformable mirror fully corrects the optics noise regardless of rms gradient, and the spec can be loosened to $100 \text{ \AA/cm}$ (or more?).

Modeling Results: NIF-sized Beam

Figure 14 shows the modeling results for a NIF-sized beam (1250 cm^2) without an adaptive optic. It shows an uncorrected spot size of $\sim 35\text{-}40$ microrad.

Figure 15 shows the same cases with an adaptive optic. From this we conclude:

- 1) Even if the adaptive optic perfectly corrects pump-induced distortions (red curves), we do not meet the NIF specifications with short scale length optics finishes from $25\text{-}100 \text{ \AA/cm}$. As above, however, if the scale lengths are long, even finishes of $100 \text{ \AA/cm}$ will be tolerable (assuming, again, Gaussian statistics).
- 2) Comparing the red and black curves, if some portion of the whole-beam self-focusing effects can be mitigated, the rms gradient requirement for even short scale length optics could be as large as $\sim 100 \text{ \AA/cm}$.

Conclusions

An rms gradient specification for long scale-length optics aberrations has been proposed by J. Downie for NIF optics. This specification format appears to provide good connection between the specification and the functional requirement of 80% of a high power beam inside a 200-250 micron diameter spot for the SSMP mission of NIF (the most stressing mission, from an optics-quality standpoint). It is especially useful under the assumption of Gaussian gradient distributions, but may be valid under other distributions; Beamlet data (individual parts and system) support this assumption.

This format is conveniently translated into random Gaussian phase screens for modeling purposes, which is necessary for setting the magnitude of the specification. Such modeling supports the claim that the rms phase gradient well-describes the uncorrected focal spot. With the addition of an adaptive optic, however, the aberrations can be more or less corrected, depending on the scale length of the aberrations, with longer-scale noise being more correctable.

The scale length parameter used in these studies is defined mathematically, or through the auto-correlation of the phase of an optic. Beamlet parts have scale lengths from 1-3 cm free-standing. The aggregate system has a scale length closer to 5 cm. The difference between these two may be due to mounting effects, or long-wavelength coherence between optics.

The three other principle contributors to spot size besides optics quality, are pump-induced distortion, whole-beam self-focusing, and the adaptive optic. There are significant uncertainties in the models for both pump-induced distortions and the adaptive optic, leading to corresponding uncertainties in the needed optics specifications. In addition, it may be possible to statically correct for the whole-beam self-focusing, which would give greater flexibility in optics requirements. Because of these uncertainties, it was not possible in this work to put a final answer on the optics requirements.

That said, however, an average-optic requirement of 30-100 Å/cm for the rms gradient appears reasonable. In addition, it appears the scale length of aberrations should be longer rather than shorter. Assuming Gaussian statistics, the adaptive optic will be much better able to correct for longer scale aberrations, which would significantly soften the rms gradient requirement.

Future work should focus on a better understanding of the pump-induced distortions for NIF, the adaptive optic, and the effectiveness of possible whole-beam self-focusing correction schemes.[WW1][WW2]

WW:dls

Absent correction, far field spot size depends only on rms gradient

FIGURE 1

Real parts have approximately Gaussian gradient distributions.

The optic-average rms gradient, estimated from a Beamlet rod shot, is $\sim 80 \text{ \AA/cm}$.

- Assume phase errors add incoherently (rss) between separate elements in the chain, but coherently in the multi-passed elements (15 four-pass elements, 10 two-pass elements, and 15 one-pass elements).
- This gives $\text{rms_gradient}_{\text{total}} = 17.2 \text{ rms_gradient}_{\text{one part}}$
- For above: $\text{rms_gradient}_{\text{total}} = 1400 \text{ \AA/cm}$, $\Rightarrow \text{rms_gradient}_{\text{one part}} = 80 \text{ \AA/cm}$.

Measured scale lengths and rms gradients.

The core of the (low power) infrared focal spot is determined by the gradient distribution; the “tails” of the focal spot are determined by the PSDs

For simulations, a Gaussian gradient distribution can be generated using a random Gaussian phase screen (something PROP92 understands).

random Gaussian phase screen: $\text{random} [-1:1] * e^{-\left(\left(\frac{x}{s_g}\right)^2 + \left(\frac{y}{s_g}\right)^2\right)}$

convolution
↓

example: rms gradient=0.2 wave/cm, $s_g=6$ cm

- The random Gaussian phase screen is parameterized by the rms phase gradient and the aberration scale size, s_g .

The overlap between the random Gaussian phase noise and the PSD files is small.

FIGURE 7

Beamlet pump-induced distortions used in modeling.

PROP92 adaptive optic

- 39 actuators, Gaussian influence functions with 8 cm 1/e radii

This modeling includes only some of the contributors to the focal spot.

Example of modeled focal spot.

without adaptive optic:

with adaptive optic:

(low power, Beamlet pump-induced distortions, $s_g=2$ cm, $50 \text{ \AA/cm}$ rms gradient)

NIF 1 ω modeling with Beamlet-sized beam (1000 cm²), without adaptive optic.

NIF 1 ω modeling with Beamlet-sized beam (1000 cm²), with adaptive optic.

FIGURE 13

NIF 1ω modeling with NIF-sized beam (1250 cm²), without adaptive optic.

NIF 1 ω modeling with NIF-sized beam (1250 cm²), with adaptive optic.

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