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Simulations of a phase corrector plate for the National Ignition Facility

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ABSTRACT

Simulations are presented on the effect of placing a static phase corrector plate in each beamline of the National Ignition Facility (NIF) to assist the adaptive optic in correcting beam phase aberrations. Results indicate such a plate could significantly improve the focal spot, reducing a 3σ , 80% spot half-angle from 21 to 8 μrad for poorer-quality optics, and 17 to 7 for better optics. Such a plate appears to be within the range of current fabrication technologies. It would have an alignment requirement of ± 0.5 mm, if placed in the front end. In NIF operation, the occasional replacement of laser slabs would slowly degrade the beam quality for a fixed corrector plate, with the spot size increasing from 8 to 15 μrad after four new slabs for poorer optics, and 7 to 12 μrad for better optics. The energy fraction clipped on the injection pinhole (± 100 μrad) would be $< 0.5\%$ due to this pre-correction.

1. BACKGROUND

NIF is currently being designed to a spot size goal of 500 TW inside a 250 μm diameter circle for its short-pulse (1 ns, temporally-flat) mission. In this study we considered a well-recognized possibility of improving the focal spot by adding a passive phase correction plate (e.g. an etched piece of fused silica) to each beamline to correct some part of the aberrations in the beam. If intended to correct aberrations which are common to all beamlines only (i.e. pump-induced distortions), there would be only one corrector design. If the correction of, especially, optics aberrations, is intended, then it would be custom-made for each beamline, and we would need 192 different designs. By contributing to the focal spot correction, such a device may ease requirements on the adaptive optic, as well as optical specifications, although these considerations have not been quantified.

The focal spot has a number of contributors, including: the optics quality, pump-induced distortions (flexing of the slab due to non-uniform irradiation by the intense flashlamp light), residual thermal distortions in slabs due to previous laser firings, non-linear phase push-back (self-focussing) of the beam, mounting errors and gravity sag of optics, air turbulence in the beam lines, and smoothing by spectral dispersion. The 39-actuator adaptive optic is able to correct much of the long-wavelength aberrations, principally those due to the pump-induced distortions, residual thermal aberrations, mounting errors and gravity sag. The other contributors contain higher frequency noise, and so are less correctable by the adaptive optic. Of these, the optics finishing errors are the largest contributor, and, being static, are amenable to a static correction technique. The pump-induced distortions are also a very repeatable aberrations (although transient in time), and so could be corrected with such a plate. Because they are readily corrected by the adaptive optic, correction by a static plate would only serve the purpose of reducing the requirements on the adaptive optic.

Because this optic is intended to correct relatively long-wavelength phase aberrations ($> \sim 1$ cm), which chiefly define the focal spot size and which can propagate through the laser chain without diffracting into amplitude modulation, the corrector plate could be placed at any point in the chain. Three likely places are as part of the diffractive optic plates in the final focus assembly; in the front end, just before injection into the transport spatial filter; or as a part of the adaptive optic face plate. The second option (placement in the front end) was considered in this modeling because of the small size requirements for such an optic, and the (assumed) lower cost.

2. SIMULATIONS

Simulations were run on a 512x512 grid for a 1 ns, temporally-flat pulse. They included pump-induced, optics finishing, and self-focusing aberrations. The other effects listed above, but not included in the model, are incompletely understood at present, but are, for a variety of reasons, expected to be smaller contributors to the focal spot. Two specific NIF optics finishing cases were considered in this analysis: a 90 $\text{\AA}/\text{cm}$ rms gradient and "nominal" waviness-1 Power Spectral Density (PSD); and a 75 $\text{\AA}/\text{cm}$ and

"nominal/2" waviness-1 PSD. The details of this specification format will not be discussed here, but the former can be considered poor quality optics; and the latter better quality optics. The current specification goal for NIF splits the difference at 75 Å/cm rms gradient and "nominal" waviness-1. The corrector plate was calculated by retrieving the phase of the low-power 1ω beam entering the converter, spatial filtering to remove aberration wavelengths shorter than 1 cm, inverting the phase sign, and decreasing its near-field dimensions to match the NIF injection magnification. This was done for five cases:

- 1) a beam having only pump-induced (i.e. active) aberrations;
- 2) a beam having only optics quality (i.e. passive) aberrations (90 Å/cm, nominal waviness-1);
- 3) a beam having only optics quality (i.e. passive) aberrations (75 Å/cm, nominal/2 waviness-1);
- 4) a beam having both passive and active aberrations (90 Å/cm, nominal waviness-1); and
- 5) a beam having both passive and active aberrations (75 Å/cm, nominal/2 waviness-1).

The filtering cut-off of 1 cm was arbitrary, and was done under the assumption that such filtering would ease fabrication. The resulting phase maps, which the correcting optic would be required to add to the beam, are shown in Figures 1-3 for the 90 Å/cm case. (The 75 Å/cm maps are very similar, but with the passive aberrations providing approximately 75/90=0.83 smaller amplitude.) The peak-to-valley phase is $\leq \sim 3$ waves (1ω), with no spatial features smaller than 1.1 mm. In simulations, this phase map was placed before the injection lens, at the same relay plane as the apodizer. Operationally, it would need to be near the injection mirror, both because of the 1:4 split (if a custom plate was made for each beamline), and because this phase induces significant near-field amplitude modulation in the front end beam which could not be tolerated in the regen or preamplifier rods.

3. DETERMINATION OF PHASE CORRECTION

If the optic is used to correct aberrations unique to each beamline in NIF, as assumed in these simulations, then consideration would need to be given to how the phase map of each beamlet in NIF could be obtained after machine assembly. One likely possibility is to use the roving pick-off mirrors and the interferometers in the diagnostic stations already planned for each switchyard.

4. FABRICATION

Fabrication of such a part appears reasonable, either with a step-etch (dry or wet) process (16 steps ?), or, possibly, with a continuous process. The substrate material could be fused silica for damage resistance.

5. RESULTS

Several cases were simulated with the different corrector plate options:

- 1) no correction,
- 2) correction with adaptive optic only,
- 3) correction with adaptive optic and a phase plate based on active (i.e. pump-induced) aberrations only,
- 4) correction with adaptive optic and a phase plate based on passive (i.e. optic finish) aberrations only,
- 5) correction with adaptive optic and a phase plate based on passive and active aberrations,
- 6) correction with adaptive optic and the corrector plate from case 5), with one replaced slab,
- 7) correction with adaptive optic and the corrector plate from case 5), with two replaced slabs,
- 8) correction with adaptive optic and the corrector plate from case 5), with three replaced slabs, and
- 9) correction with adaptive optic and the corrector plate from case 5), with four replaced slabs.

Figure 4 shows the 50%, 80%, and 95% spot sizes in 1ω and 3ω for the poorer quality optics. (The 50% spot size is, for example, the spot half-angle radius which encompasses 50% of the beam energy.) The 80%, 3ω spot size ranges from 29 μrad for the uncorrected beam to 8 μrad for a beam corrected with adaptive optic and active+passive corrector plate (case 5). With only an adaptive the spot size is 21 μrad. These results show the significant potential a corrector plate has for improving even relatively poor optics.

A comparison of cases 2 and 3 in Figure 4 indicates there is little motivation to develop a corrector plate which corrects only pump-induced aberrations (i.e. one corrector for all beamlines) because the adaptive optic corrects well these terms. Also of note is the variable increase in spot size on frequency conversion, depending on amount of correction. For the well-corrected cases, the 3ω 80% spot is twice as large as the 1ω spot. Similarly, the 1ω 95% spot size is noticeably effected by the corrector plate, whereas the 3ω spot is almost unchanged. There is a subtle interplay between the amount and frequency range of phase correction, and its effect on spot size growth on conversion.

The replacement slabs in cases 6-9 were, calculationally, new random sets of optical aberrations without recalculating the corrector plate. They correspond to the operational reality of needing to replace optics on occasion. There is a significant enlargement in the 3ω spot size, from 8 to 14 μrad with the replacement of four slabs. Little is currently known about the anticipated replacement frequency of NIF optics.

Mis-alignment of the correction optic with the beam is also of concern. Figure 5 shows the spot sizes as a function of mis-registration in the horizontal direction, from 0 to 2 mm for the poorer quality optics case. The spot increases significantly if the optic is mis-registered by more than ± 0.5 mm. This concern could be lessened further if the corrector plate, rather than being in the front end, were a part of the adaptive optic, because this mirror is already a centering reference.

Clipping of the pre-corrected beam by the injection pinhole was considered. In these simulations, with a flat-phase front end, the un-corrected beam clips $< 10^{-4}\%$, as expected. The pre-corrected beam experiences a 0.5% energy clipping. This is a negligible amount, and is small because the correction only contained phase scales within the bandpass of the pinholes (1 cm, or 100 μrad).

Similar results are shown in Figures 6 and 7 for the case of better quality optics. The 80% 3ω spot size is seen to decrease from 17 μrad with only the adaptive optic to 7 μrad for the case of the active+passive corrector and adaptive optic. The spot size increases to 12 μrad after replacement of four slabs. The alignment tolerance is still ± 0.5 mm.

These results indicate that a corrector plate can, conceptually, correct a range of aberrations equally well. This suggests that NIF may be able to consider poorer quality optics (cost savings) if we are forced to use a corrector plate.

6. CONCLUSIONS

Based on these preliminary numerical studies, use of a custom phase correction optic for each beamline of NIF appears promising as a method to improve the focal spot size and to possibly lessen the requirements on optics specifications and the adaptive optic. Such an optic placed in the front end is reasonably robust to misalignment and replacement of optics in operation, and need not introduce significant beam clipping on early pinholes.

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Figure 1. Phase correction added to the front end beam by the corrector plate for the case of active (pump-induced) aberration precompensation.

Figure 2. Phase correction added to the front end beam by the corrector plate for the case of passive (90 Å/cm optics quality) aberration precompensation. (The 75 Å/cm plate is identical, with $75/90=0.83$ smaller amplitude.)

Figure 3. Phase correction added to the front end beam by the corrector plate for the case of passive (90 Å/cm optics quality) and active (pump-induced) aberration precompensation.

Figure 4. The 1ω and 3ω 50%, 80%, and 95% spot sizes with varying levels of correction, and with replacement of slabs in operation for the **90 Å/cm, nominal waviness-1** case. The adaptive optic was allowed to correct as much as possible the aberrations from the replacement slabs.

Figure 5. The sensitivity of the 1ω and 3ω 50%, 80%, and 95% spot sizes with misalignment of the beam in the horizontal direction in the front end for the $90 \text{ \AA/cm}$, nominal waviness-1 case.

Figure 6. The 1ω and 3ω 50%, 80%, and 95% spot sizes with varying levels of correction, and with replacement of slabs in operation for the $75 \text{ \AA/cm}$, nominal/2 waviness-1 case. The adaptive optic was allowed to correct as much as possible the aberrations from the replacement slabs.

Figure 7. The sensitivity of the 1ω and 3ω 50%, 80%, and 95% spot sizes with misalignment of the beam in the horizontal direction in the front end for the **75 Å/cm, nominal/2 waviness-1** case.