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R. E. English, Jr.
L. G. Seppala
C. S. Vann
E. S. Bliss

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R. Edward English Jr., Lynn G. Seppala, Charles S. Vann, and Erlan S. Bliss

Lawrence Livermore National Laboratory
Post Office Box 5508, Livermore, CA 94551
Phone: (510) 422-5483, FAX: (510) 422-1930

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ABSTRACT

The conceptual design of the National Ignition Facility (NIF) 192 beam laser incorporates a low-power alignment beam injected in the pinhole plane of the final spatial filter with a wave length intermediate between the 1053 nm laser output and the 351 nm frequency-converted beam that illuminates the target. Choosing the specific wavelength for which the spatial filter plane is reimaged in the same target chamber plane as the frequency-converted main laser pulse, achieves optimum accuracy without the need for additional means to insure precise overlap between the two beams. Insertion of the alignment beam after the last laser amplifier also allows alignment to the target while the amplifiers are still cooling from a previous shot.

Key words: automatic alignment, fiber optics, fiber splitters, inertial confinement fusion, laser alignment, National Ignition Facility, target alignment

1. NIF REQUIREMENTS FOR BEAM POSITION ON TARGET

Preparations for a target shot on NIF must be expeditious and accurate. System design requirements specify 2 hours or less for all beam control and laser diagnostics functions with a final lateral accuracy on target of 50 µm (rms over all 192 beams) and focus accuracy of 1 mm. Approximately 10 µm of the 50 µm lateral error budget and half of the 1 mm focus error budget are allocated to representation of the pulsed beam by the alignment beam. As discussed in a companion paper,[1] these requirements combined with cost and reliability constraints imply an automated system that minimizes laser power requirements, the number of moving parts, and interference with other systems.

2. NIF BASELINE DESIGN FOR A TARGET ALIGNMENT BEAM

Two absolute references for alignment of focused light in the high power NIF laser system are the pinhole in the final spatial filter of each beam, where the wavelength is 1053 nm, and the target illuminated by all the beams, where the wavelength is 351 nm. The optics between these two locations are designed to accurately relay an image of the first reference point onto the second while accounting for the wavelength conversion of the main beam and longitudinally and laterally displacing the residual 1053 and 526.5 nm light away from the target. The lateral separation of wavelengths at the target is achieved by the dispersive properties of a wedge in the final focus lens while the longitudinal separation results from the focal length dispersion of that lens.

A low power alignment beam of any wavelength can be injected in the region of the final pinhole. In the general case, the injection point has to be offset both laterally and longitudinally from the pinhole to be reimaged at the correct position on the target. The lateral part of the two dimensional offset must be done with great precision, because the 10 µm error budget noted in Section 1 above includes several effects in addition to the accuracy of insertion. As the longitudinal distance from the 1053 nm focus increases, the centerline position from which to measure the lateral injection offset becomes ambiguous, so the highest accuracy of injection is achieved by choosing the unique alignment wavelength that eliminates the longitudinal offset.

Figure 1 illustrates this alignment concept. For the NIF Conceptual Design Report (CDR) design, at a wavelength of approximately 389 nm, the effects of longitudinal dispersion in the spatial filter lens and final focus lens cancel; thus, the alignment beam focuses at the same distance from the focus lens as the 351 nm shot beam. Lateral dispersion due to wedges in the delivery system (principally the off-axis focus lens) is not compensated. However, because the injection point is now entirely in the plane of the pinhole, the required lateral offset can be accomplished with sufficient accuracy.

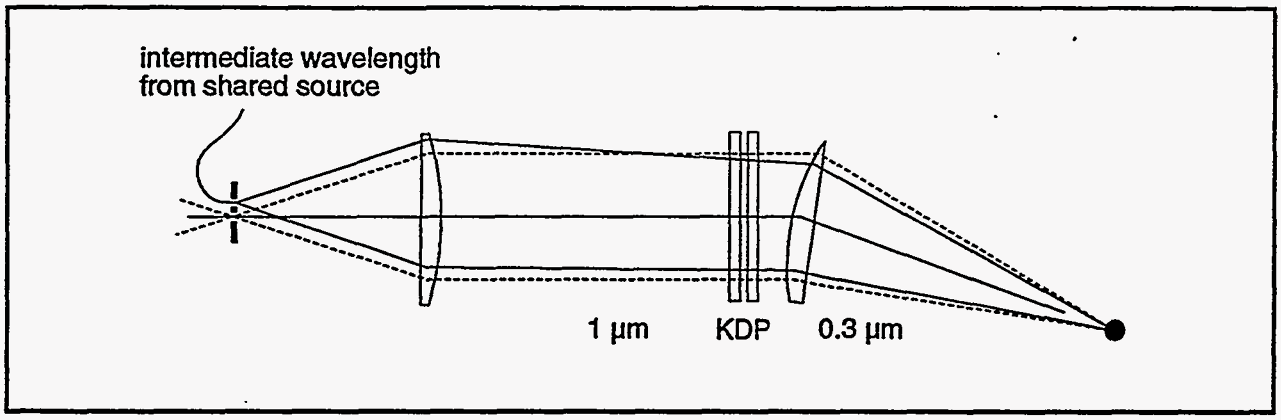

Figure 1. There is a particular value of wavelength for which the pinhole plane of the last spatial filter is reimaged at the target position with no longitudinal offset.

The unique value of intermediate wavelength is dependent on the optical design of the laser system. In particular, it varies with the focal lengths of the lenses, the spacing between them, and the dispersion properties of the lens material. Equation (1) is the analytic expression relating the variables, where f_1

$$0=f_1\left(\frac{n_3-n_i}{n_3-1}\right)+f_3\left(\frac{n_1-n_i}{n_1-1}\right)+L\left(\frac{n_3-n_i}{n_3-1}\right)\left(\frac{n_1-n_i}{n_1-1}\right) \tag{1}$$

is the focal length of the output spatial filter lens at 1053 nm; f_3 is the focal length of the final focus lens at 351 nm; L is the distance between the lenses; and n_1, n_3, and n_i are the indices of refraction of the lens material at 1053 nm, 351 nm, and the intermediate wavelength respectively. One can solve this equation for n_i and then convert to wavelength using the known dispersion curve for the lens dielectric.

Figure 2 is a plot of the intermediate wavelength versus the ratio of the focal lengths for two limiting cases assuming that the material for both lenses is fused silica. One limit corresponds to the maximum reasonable spacing between the lenses, namely two times the spatial filter lens focal length. For a spatial filter magnification of unity, an image of the output plane of the last amplifier before the spatial filter would be relayed to the plane of the KDP frequency conversion crystals. The other limit is for the case in which the spacing of the lenses approaches zero. All functional system designs fall between these limits.

The extent of lateral offset Δx required at the injection point of the intermediate wavelength beam is related to the same parameters by equation (2), where α is the wedge angle at the center of the lens.

$$\Delta x=\left[L\left(1-\frac{n_i-1}{n_1-1}\right)+f_1\right]\left[\sin^{-1}(n_3\sin\alpha)-\sin^{-1}(n_i\sin\alpha)\right] \tag{2}$$

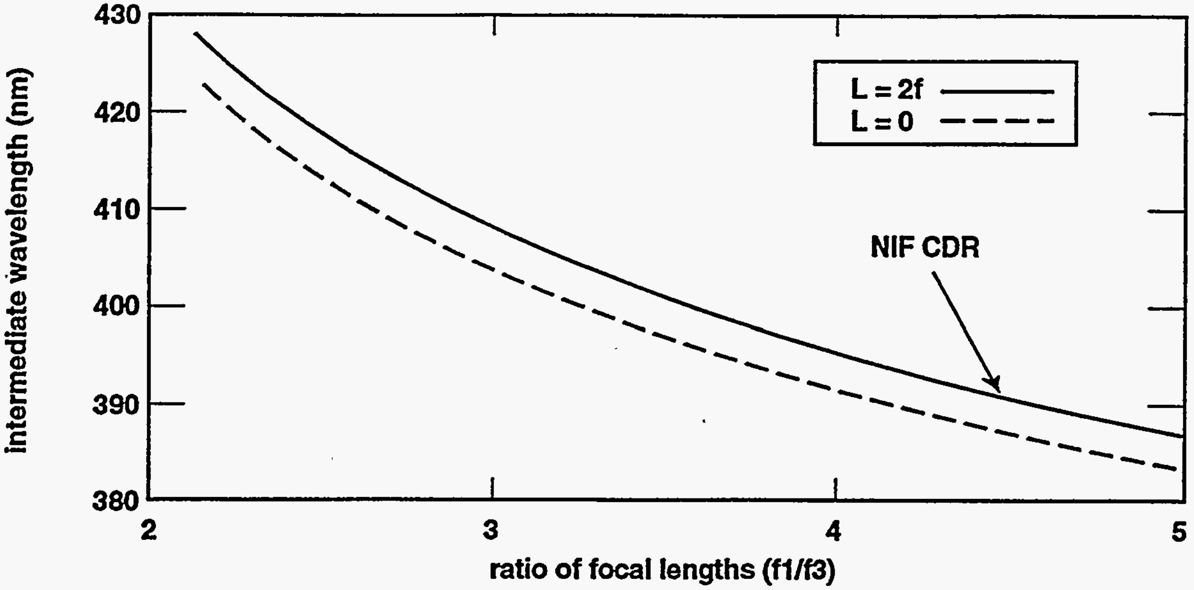

Figure 2. Intermediate wavelength vs. focal length ratio assuming a 7 m final focus lens.

3. SENSITIVITY TO LASER SYSTEM PARAMETERS AND OTHER DESIGN FEATURES

Practical application of this target alignment concept depends on the existence of reasonable sensitivities to design, material, and fabrication parameters. One can explore these sensitivities with the same two equations. Table I summarizes some important examples.

Table I. Parameter variations causing alignment errors comparable to error budget allowances for the NIF CDR laser design

NIF beam-delivery-system parameters	
effective focal length of output spatial filter lens (f_1)	32.50 m
effective focal length of final focus lens (f_3)	7.00 m
representative lens separation (L)	62.00 m
intermediate wavelength (λ_i)	389 nm
lateral offset of intermediate wavelength injection point	10.82 mm
final focus lens wedge angle (α)	67.41 mr (3.86°)
Changes that cause a ± 7 μm beam position error on target	
final focus lens index change (Δn_i)	$\pm 14.8 \times 10^{-6}$
alignment laser wavelength change ($\Delta\lambda_i$)	± 0.12 nm
final focus lens wedge angle change ($\Delta\alpha$)	± 0.19 mr (38 sec)
injection point lateral offset change	± 32 μm
Changes that cause defocus of ± 0.25 mm on target	
either lens index of refraction change (Δn)	$\pm 14.4 \times 10^{-6}$
either lens focal length change (Δf)	± 0.3%
alignment laser wavelength change ($\Delta\lambda_i$)	± 0.12 nm
lens separation change (ΔL)	± 2.08 m

On the NIF system, there are three or four 1053 nm transport mirrors on the path from the output spatial filter lens to the final focus lens. Using an intermediate wavelength beam for alignment to the target requires that these mirrors also reflect enough of the λ_i light to keep the power requirements for the intermediate wavelength laser reasonable. Our standard high reflectivity coatings are designed for use over a range of angles. Therefore, at a fixed angle they have high reflectivity over a corresponding range of wavelengths, as illustrated in Figure 3. Furthermore, such coatings also tend to have high reflectivity over a reduced range around 1/3 of the design wavelength. When dispersion in the coating materials is taken into account, however, the shorter wavelength band shifts toward 389 nm. A satisfactory transport mirror coating must have predictable partial reflectivity at both 351 and 389 nm, and work is ongoing to identify suitable coating design tradeoffs.

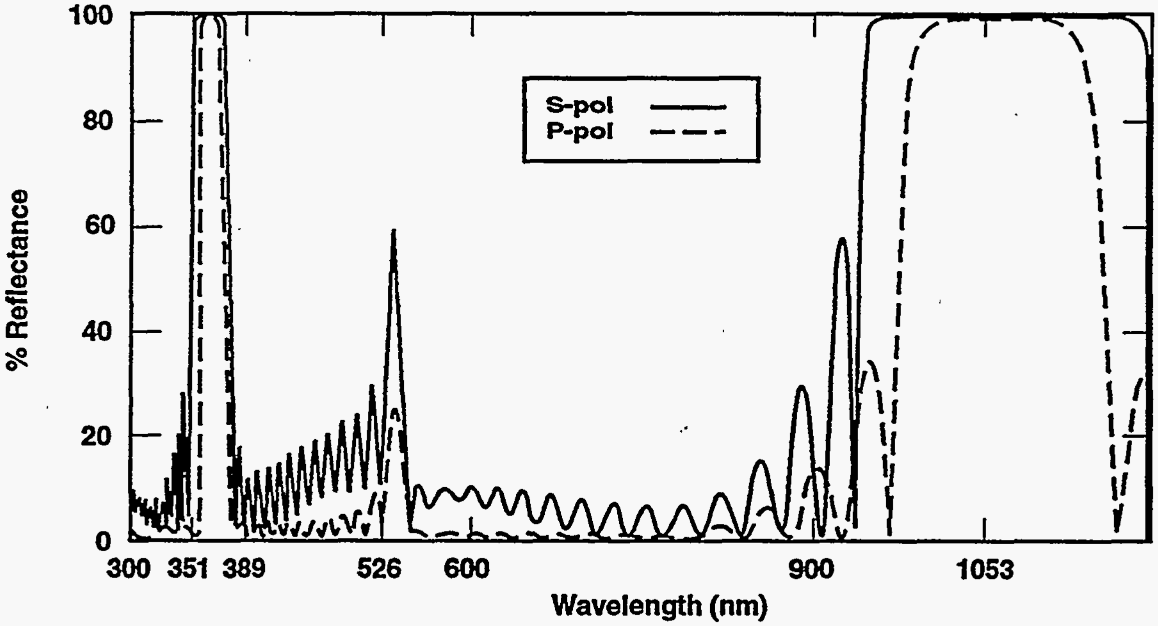

Figure 3. The harmonic spectral response of a 1053 nm high reflectivity coating is naturally biased toward the required 389 nm intermediate wavelength. The coating illustrated here has additional layers added to increase the reflectivity at 526 nm.

The essence of the intermediate wavelength alignment design is that the alignment beam can be injected in the final spatial filter with no longitudinal offset. Injection in the final spatial filter is very beneficial because the beam can be used immediately after a shot without concern for the thermally induced aberrations in the laser chain. One might think of the lateral offset that remains as an annoyance that must be tolerated. In fact, it provides a significant operational advantage in that the mirror used to inject it does not block the path of 1053 nm light from the laser. Therefore, after the laser chain has recovered from the preceding shot, alignment tasks that require 1053 nm light and those that use the intermediate wavelength beam can take place simultaneously.

Laser sources at the required wavelength are available commercially. For example, a frequency doubled diode laser or Ti:sapphire laser could not only provide the currently identified wavelength, but could also be tunable over a range that would include the requirements of alternate NIF system parameter choices. Although the cost and complexity of a fully engineered tunable source strongly suggest the use of fiber fan-out distribution systems to serve many beam lines from each laser source, single mode fibers and fiber splitters for this wavelength range are not presently available and will require development.

3. SUMMARY

The NIF laser system incorporates frequency conversion of the optical wavelength of each beam immediately before it enters the target focusing optics. The proposed target alignment system uses a beam that is injected in the plane of the final spatial filter pinhole and automatically reimaged in the target chamber in the same place as the frequency converted laser output pulses. This avoids the requirement imposed by alternate approaches, such as injection of a 351 nm alignment beam, to use costly large aperture beam sampling optics and diffraction limited pointing sensors to assure that the alignment beam is launched correctly.[2,3] In addition, the spatial-filter-plane injection point supports the use of output alignment immediately after a system shot, and the offset of the injection from the main beam axis allows simultaneous laser and target alignment operations.

4. ACKNOWLEDGMENTS

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