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MASTER

TITLE PHASE ABERRATIONS AND BEAM CLEANUP TECHNIQUES IN CARBON-DIOXIDE LASER FUSION SYSTEMS

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Phase aberrations and beam cleanup techniques in carbon-dioxide laser fusion systems*

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Abstract

This paper describes the various carbon dioxide laser fusion systems at Los Alamos from the point of view of an optical designer. The types of phase aberrations present in these systems, as well as the beam cleanup techniques that can be used to improve the beam optical quality, are discussed. As this is a review article, some previously published results are also used where relevant.

Introduction

The carbon dioxide laser fusion systems at Los Alamos are the Gemini,[1] Helios,[2] and Antares[3] laser systems. The first two are currently operational and are being used for target experiments. Antares is currently under construction. Typically, the Los Alamos CO_2 laser fusion systems consist of a master oscillator and electro-optic switchout which produce a subnanosecond pulse. This pulse is directed through preamplifiers, beam splitters, and a double- or triple-pass amplifier. The amplified beams then enter the target chamber and are focused onto a target. In the subsequent sections of this paper, as an example, the Helios laser system is described in some detail. The optical parameters of interest in laser fusion systems are discussed, as well as the reasons for degradation in optical performance. The analysis scheme used at Los Alamos is briefly described, and the calculated and experimentally obtained results in the case of Gemini, Helios, and the Gigawatt lasers are discussed. The phase aberrations present in these systems, as well as schemes for improving the optical performance through the use of better components, spatial filters, and adaptive optics elements, are described.

Description of the Helios laser system

The Helios system is somewhat typical of the Los Alamos CO_2 laser fusion systems, especially from the point of view of the optics. The Helios optical system is schematically shown in Fig. 1. It contains more than 100 optical elements in 8 identical paths, each about 120 m long. Figure 2 shows the optical schematic of one of the eight beams in the Helios system. (The other seven beams are optically similar.) A nominal nanosecond pulse is switched out of a TEA oscillator through a three-stage CdTe Pockels cell array which acts as an electro-optic switch. It then undergoes three stages of preamplification and beam splitting before entering the final amplifier. Figure 3 shows the optical schematic and the beam path through one of the final amplifiers all the way to the target plane. Optically, the final amplifier is a triple-pass 17X afocal off-axis Gregorian telescope. A 100 mJ, nearly 2 cm collimated beam enters the triple pass amplifier and increases in energy to nearly 1 J in the first pass. It then strikes a turning mirror and is focused at the spatial filter. The beam then diverges and is deflected by another flat turning mirror, and its energy in this second diverging pass reaches nearly 300 J. Double passing the saturable absorber cell and the salt window (element No. 5 in Fig. 3) reduces the energy to about 150 J. The ~34-cm-diam collimated beam then makes a third amplification pass, and the energy reaches nearly 1200-1500 J. The collimated beam is then brought to focus by an off-aperture parabola producing an f/2.4 beam at the target. Throughout most of the system, the beam size is roughly 2-2.5 cm in diameter. However, during the second pass through the final amplifier, the beam diameter increases to nearly 34 cm and retains this size till it is focused at the target to a spot ~120 μm diameter.

From a geometrical optical design point of view, the system consists of a series of nearly 1X afocal telescopes, some with lenses on axis and a few with off-axis spherical mirrors. This is followed by a 17X Gregorian telescope, and the expanded beam is brought to focus by a parabola. The field angle is zero, and the tilt of the mirrors is quite modest. Except for the final focusing parabola (where the f/number is 2.4), the rest of the system has large f/numbers. Hence, geometrical raytraces of the system (neglecting alignment and component errors) would show negligible aberrations, and evaluation techniques based on raytracing techniques would predict a diffraction-limited system.

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However, this approach is valid only for the initial layout of the system. Other factors (such as diffraction propagation of the beam, intensity alterations due to coherent and nonlinear effects, and effects of spatial filters) limit the usefulness of geometrical techniques severely. The only effective way of designing and understanding these systems appears to be to propagate the amplitude and phase of the beam through the various components and distances, taking into account diffraction and other modifications due to imperfect components, various apertures and spatial filters, as well as any nonlinear effects that exist.

Design considerations for CO$_2$ laser fusion systems

There are five major considerations in optical design of laser fusion systems.[4] Again, taking Helios as an example, the optical apertures have to be chosen to avoid damage to windows and mirrors. In addition, the size of the salt window that could be successfully manufactured limits the maximum aperture size to ~34 cm. From this, the design goal of 10 kJ determines the number of final amplifiers in the system. Second, the pressure, volume, and gain coefficients within the final amplifier modules are chosen to meet operating requirements. The third consideration is suppression of parasitics and control of amplified target backscatter. These considerations involve judicious use of the geometrical layout of the optical subsystems, as well as use of spatial filters, not only to improve the image quality, but also for retropulse protection of the optical components. An interesting example is the use of the spatial filter in the dogleg of the triple-pass amplifier. For the forward pulse, this spatial filter acts to cleanup the beam. The 17X telescope becomes a 17X compressor for the backscattered beam from the target. The energy density gets quite high and can damage the optical components. So, the same spatial filter region is used for optically induced gas breakdown purposes to prevent damage. The fourth consideration is that the focused beam quality, pulse duration, and contrast ratio of the pulses produced be compatible with the needs of the target experiments. This involves, among other considerations, the proper geometric layout of the system, components with an acceptable quality level, and the use of spatial filters to improve the beam quality. Finally, the individual beams have to be pointed and focused on fusion targets within the experimental requirements of ±20 µm. This has implications for the assembly, stability, and alignment of the whole system.

Optical performance of CO$_2$ laser fusion systems

In this section, the optical parameters of interest, the reasons for degradation in optical performance, the analysis scheme, the performance characteristics, and the possible levels and types of aberrations present in these types of systems are discussed.

Although laser fusion systems resemble conventional systems, which form an aerial image in the focal plane, their purpose is to couple the energy to the target. Consequently, the modulation transfer function values are not of direct interest, and the optical parameters of interest are the Strehl ratio, irradiance, and encircled energy distributions. At Los Alamos, these parameters are computed by propagating the amplitude and phase of the laser beam through the entire system, taking diffraction into account as well as the effects of imperfect components and other nonlinear effects that occur in the system.[5] The codes that are used to implement this computational procedure are FRINGE[6] and [illegible][7].

As pointed out earlier, with perfect components, these systems tend to have diffraction-limited performance. The degradations arise mostly due to imperfections in the large components in the system and alignment errors. The average alignment error for a beam in Helios has been shown experimentally[8] to be 34 µm, which is close to the target requirements. Figure 4 shows the computed Strehl ratio for one of the segments of the Helios system. Spatial filter 5 in Fig. 4 is the spatial filter in the dogleg of the triple-pass amplifier (Fig. 3). The Strehl ratio at this station is 0.98, and all the degradation occurs between this station and the target plane where the large optical elements occur in the system. In the computation, a λ/10 peak-to-valley (p-v) error was assumed for the optical path difference (OPD) introduced by each of the optical elements in the nominal system. The actual elements occurring in the Helios system before this spatial filter actually were contributing closer to λ/20 p-v in error.

Figure 5 shows the results for the Helios system. Curve A represents the diffraction-limited case. Curve B represents the computational curve assuming a p-v error of λ/10 OPD introduced by each optical element in the system. Curves C and D represent the computational and the experimentally obtained results for one of the best beam lines in Helios. Curves E and F represent the computational and experimentally obtained results[9] for one of the worst beam lines in Helios. Figure 6 shows the optical schematic of the Gemini system. A nominal nanosecond pulse is switched out of the TEA oscillator. This pulse undergoes two stages of preamplification and reaches about one joule. It is then split into two beams which are amplified to full power in a large, electron-beam-controlled, high-pressure, dual-beam-module amplifier. These beams are brought to focus by an off-aperture parabola. Figure 7 shows the computational and experimentally obtained results for the Gemini system. These results show reasonable agreement between the computations and the experimental results. The general level of aberrations existing in the wavefront is ~2λ at 10.6 μm, with 75% of it due to the large salt windows in the system and the rest due to spherical aberration, mostly.

Schemes for improving the optical performance

As pointed out before, these systems can be designed to be perfect systems from the conventional geometrical optics point of view. The degradations occur in the assembly alignment, and the use of novel optical components that are large in size (16-inch-diam turned-copper flat and powered surfaces, NaCl windows, etc.). There are basically three approaches to improving the performance. The first is the use of spatial filters. This is dramatically shown in Fig. 4 where the Strehl ratio rises from 0.45 to 0.98 at Spatial Filter 5 (one Airy disc size in diameter). However, Fig. 4 also shows that this is effective only up to that point in the system. The succeeding large elements drop the correction level dramatically and, consequently, this technique can work only up to a point. The second technique involves using better components. This is illustrated in Fig. 5. The set of curves E and F show a Strehl ratio of 0.2; the curves C and D show a Strehl ratio of 0.4, and the improvement in performance of the latter set is due to the improved quality of the double-passed saturable absorber salt. Thus, component improvement can play a role in better performance. However, as curve B shows, there is a definite upper limit that can be attained using practical components (each element contributing λ/10 error to the wavefront at random). The last technique involves using a deformable optical element. Figure 8 shows the effect of using a deformable mirror with 19 actuators[10] to improve the beam quality. This mirror was designed to replace the collimating mirror in the Gemini final amplifier, and was manufactured by the Hughes Aircraft Company. The lower curve depicts the performance of the Gemini laser system (Strehl = 0.24), and the upper curve shows that the performance reaches the diffraction limit (Strehl = 0.99)

Conclusions

The phase aberrations present in the Los Alamos CO_2 laser systems appear amenable to correction through the three methods described above. Use of the deformable mirror appears to promise the most dramatic improvement. However, the practicality of using such a mirror in an actual laser fusion system is yet to be demonstrated.

References

1. Gemini is the two-beam CO_2 laser fusion system currently operational at Los Alamos. It is being used for inertial confinement fusion research experiments.

2. Helios is an eight-beam, subnanosecond-pulse, 15-TW CO_2 laser system and target facility for the study of laser fusion processes and is currently operational at Los Alamos.

3. Antares is a 24-beam, 40-kJ, pulsed CO_2 laser currently under construction at Los Alamos.

4. R. L. Carlson, J. P. Carpenter, D. E. Casperson, R. B. Gibson, R. P. Godwin, R. F. Haglund Jr., J. A. Hanlon, E. L. Jolly, and T. F. Stratton, "Helios: A 15-TW Carbon-Dioxide Laser Fusion Facility," Los Alamos National Laboratory (submitted to Journal of Quantum Electronics.)

5. V. K. Viswanathan, "Optical Design and Analysis of Carbon Dioxide Laser Fusion Systems Using Interferometry and Fast Fourier Transform Techniques", Proc. of the Los Alamos Conference on Optics '79, SPIE Volume 190 (1979), pp. 158-164.

6. FRINGE is an interferogram reduction program developed by J. Loomis, while he was at the Optical Sciences Center, University of Arizona.

7. LOTS (Laser Optical Transport System) is a laser beam propagation code developed by G. Lawrence, while he was at the Optical Sciences Center, University of Arizona.

8. I. Liberman and R. F. Benjamin, "Alignment Accuracy of the Helios CO_2 Laser," Proc. of the SPIE Vol. 179 (1979), pp. 67-74.

9. See article by I. Liberman in the "Digest of Topical Meeting on Inertial Confinement Fusion," (Optical Society of America, 1980), Paper TUB/10.

10. V. K. Viswanathan, J. V. Parker, T. A. Nussmeier, C. J. Swigert, W. King, A. S. Lau, and K. Price, "Use of Adaptive Optics Element for Wavefront Error Correction in the Gemini CO_2 Laser Fusion System," Proc. of the Los Alamos Conference on Optics '79, SPIE Vol. 190, (1979), pp. 251-257.

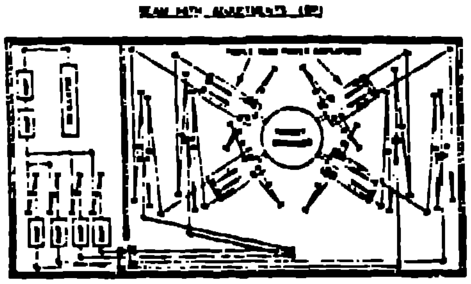

Fig. 1. Optical schematic of Helios laser.

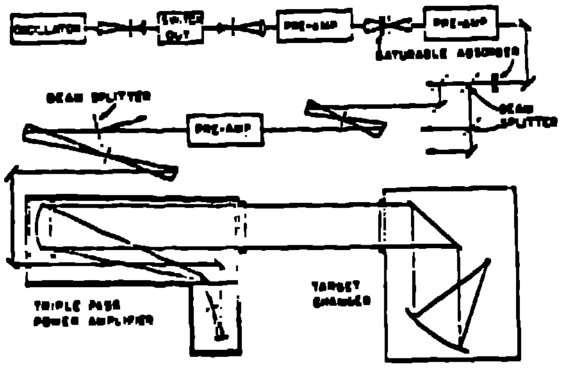

Fig. 2. Optical schematic of one of the eight beams in Helios.

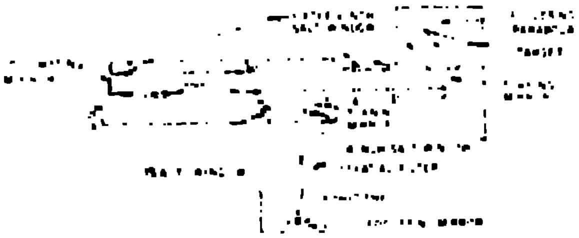

Fig. 3. Final amplifier-target region schematic.

Fig. 4. Strehl ratio through one of the beam chains in Helios.

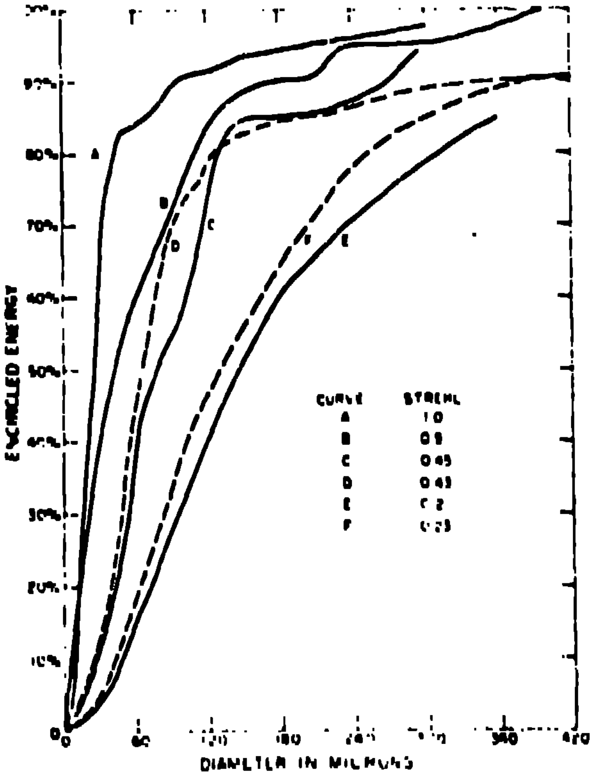

Fig. 5. Computed and experimental Strehl values for Helios beams.

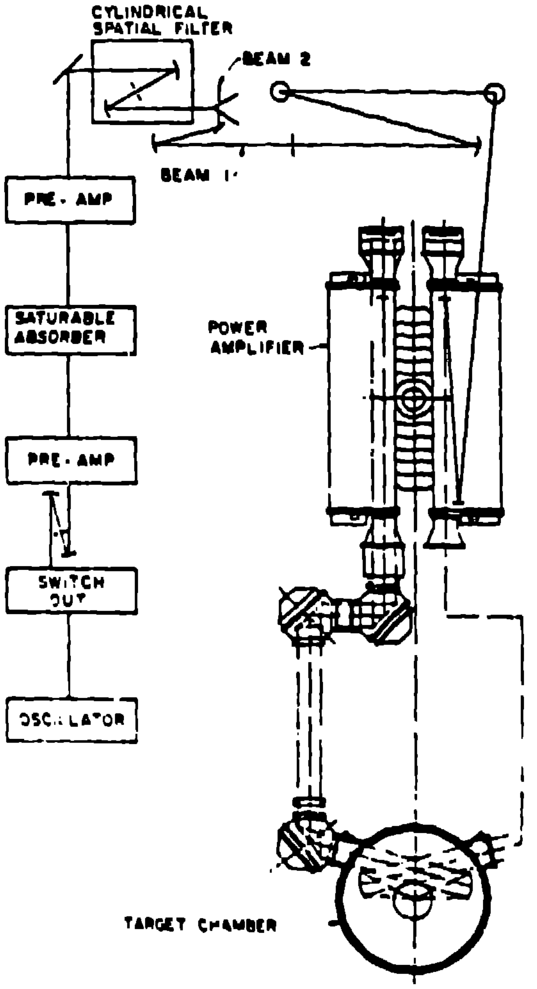

Fig. 6. Gemini laser optical schematic.

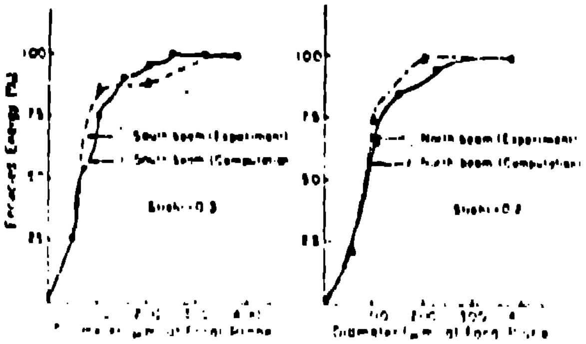

Fig. 7. Computational and experimental results for Gemini laser.

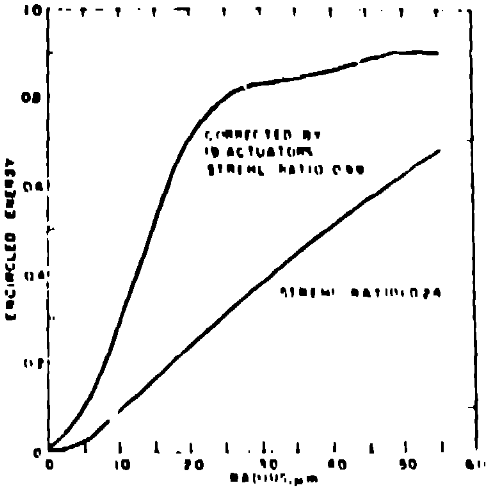

Fig. 8. Improvement due to deformable mirror.