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OMEGA: A SHORT-WAVELENGTH LASER FOR FUSION EXPERIMENTS

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Abstract

The OMEGA, Nd:glass laser facility was constructed for the purpose of investigating the feasibility of direct-drive laser fusion. With 24 beams producing a total energy of 4 kJ or a peak power of 12 TW, OMEGA is capable of nearly uniform illumination of spherical targets. Six of the OMEGA beams have recently been converted to short-wavelength operation (351 nm). In this paper, we discuss details of the system design and performance, with particular emphasis on the frequency-conversion system and multi-wavelength diagnostic system.

I. Introduction

In the direct-drive approach to laser fusion, a spherical target is irradiated by a number of overlapping laser beams as shown in Fig. 1. Compression and heating of the target are the result of the ablation pressure generated when laser energy is deposited on the surface of the target. To achieve thermonuclear ignition, the fuel inside the target must be compressed to densities in excess of 200 gm/cm^3 at temperatures higher than 4 keV. To achieve such a high compression, the drive pressure on the target must be uniform to less than ± 1%.[1] OMEGA was constructed for the purpose of investigating the feasibility of direct-drive laser fusion. OMEGA is capable of nearly uniform illumination of spherical targets.

During the last decade a number of laser-target experiments have demonstrated that laser energy is most effectively coupled to targets when the laser wavelength is shorter than 530 nm.[2-6] Using a high-efficiency, frequency-tripling system, devised and first implemented at the Laboratory for Laser Energetics (LLE),[7,8] we have modified OMEGA to operate at a wavelength of 351 nm, as well as at the fundamental wavelength of 1054 nm. In Section II of this paper, we present a brief description of the OMEGA laser facility and its 1054-nm performance.

The OMEGA frequency-conversion system and its performance are discussed in Section III. In Section IV, we briefly discuss the current status of laser-fusion research and the significance of the ultraviolet capability on OMEGA to the future of this field.

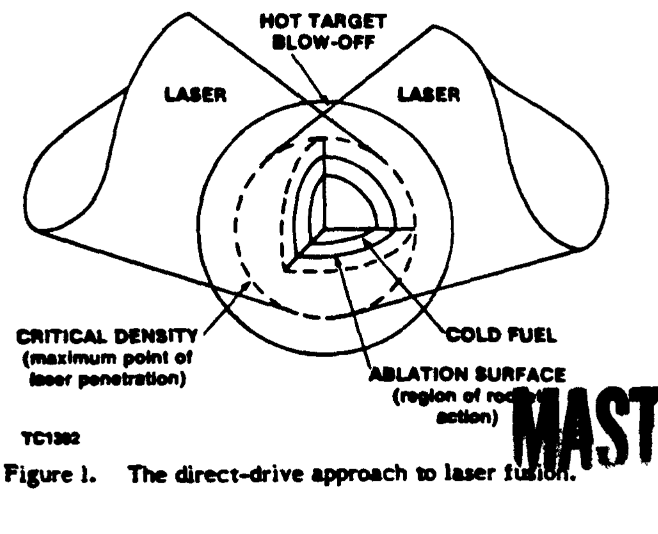

Figure 1. The direct-drive approach to laser fusion.

II. The OMEGA Laser System

The design of the OMEGA, Nd:Glass laser was driven by the following objectives.

a) Peak power capability in excess of 10 TW in short pulses (50 ps).

b) Maximum energy capability in excess of 3 kJ in 1-ns pulses.

c) A high degree of irradiation uniformity (±10%) on spherical targets.

d) A firing repetition rate of 2 shots per hour.

e) A pulse contrast ratio of greater than 10^9.

A 24-beam design was developed that achieved all of the stated objectives. The principal features of this design are discussed in the subsections below.

Laser Glass

A phosphate glass (LHG-8) was evaluated and used for OMEGA.[9] This glass has a lower, non-linear index of refraction, higher-specific gain, and lower, thermally induced optical distortion than the silicate glasses used in most glass-laser systems constructed in the 1970's. OMEGA was the first (1979) high-power laser system to use the new phosphate glass. The data obtained during testing and operation were valuable to the development of laser systems since the late 1970's.

Amplifiers

Rod amplifiers with a maximum aperture of 90 mm are used in OMEGA. This choice was driven by the dual needs to minimize operations and maintenance costs and maximize the shot rate of the facility. The rod amplifier design details are given in Ref. 9. The total bank energy of OMEGA is 4 MJ. Since 1-ns pulses with maximum energy of 4 kJ can be delivered, the overall efficiency of OMEGA is 0.1%.

Spatial Filters

Spatial filters are used in OMEGA to relay the oscillator pulse throughout the laser and to reduce small-scale intensity fluctuations that might otherwise cause non-linear beam breakup due to self-focusing. A staging diagram of the system is shown in Fig. 2. The system begins with a driver line, composed of an oscillator and four amplifiers (maximum aperture of 64 mm); the driver is split into six beams and then re-amplified by a set of six, 64-mm amplifiers. An additional four-way split results in a total of 24 beams. Each of these beams is amplified by a third, 64-mm amplifier and by a final 90-mm amplifier.

Beam Energy Control

Energy balance of the 24 beams is achieved by varying the polarization of each beam before each set of beamsplitters. Precise control of polarization by means of λ/2 and λ/4 waveplates has resulted in beam-to-beam energy balance deviations no larger than ±5%.

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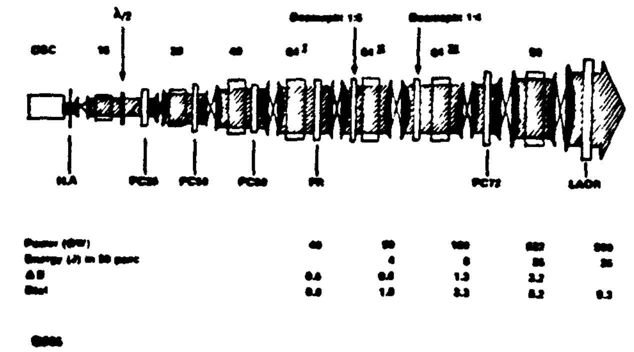


Figure 2. OMEGA staging diagram showing all essential optical elements of one beamline.

Table I

OMEGA 1054-nm Performance Summary

Short-Pulse Mode	
Pulse Duration	50 ps (FWHM)
Peak Power	12.2 TW
Minimum Spot Size	100 μm
Long-Pulse Mode	
Pulse Duration	1000 ps (FWHM)
Peak Energy	3000 J
Minimum Spot Size	30 μm
Beam-To-Beam Energy Balance	±5%
24-Beam Illumination Uniformity	±10%
Prepulse Energy	$<3\times10^{-8}$ J
Amplified Spontaneous Emission	$<2\times10^{-6}$ J/beam
System Firing Rate	1 shot/28 min

1054-nm Performance

OMEGA has been operating as a 24-beam system since January 1980. Prior to its 24-beam activation, it operated in a six-beam mode for a period of one year. Summarized in Table I are the 1054-nm performance characteristics as of May 1983.

The reliability of the system during the last two years has been exceptional. More than 3,500 shots have been fired by OMEGA during the period September 1981 to September 1983. More than 1,000 of these shots have been on target.

III. The OMEGA Frequency Conversion System

Design Considerations

The conversion of OMEGA beams to ultraviolet operation entailed decisions on issues such as:

a) location of frequency-conversion cells,

b) construction and alignment of frequency-conversion cells,

c) pointing, focusing, and beam-timing system for ultraviolet beams, and

d) beam-diagnostic systems.

The OMEGA geometry (see Fig. 3) allows two basic locations for the conversion crystals: a) at the focus lens and b) at the output of the last spatial filter (C/LAOR). C refers to the final, 90-mm rod amplifier of the laser system and LAOR refers to the large-aperture optical retarder used in the 1054-nm operation of the system.

Placing the frequency-conversion crystals near the target chamber presents two advantages over the LAOR option:

a) high-power, blue-beam propagation is limited to less than 1 meter, and

b) the focus lens and blast shield are the only optics subjected to high, blue-beam fluxes.

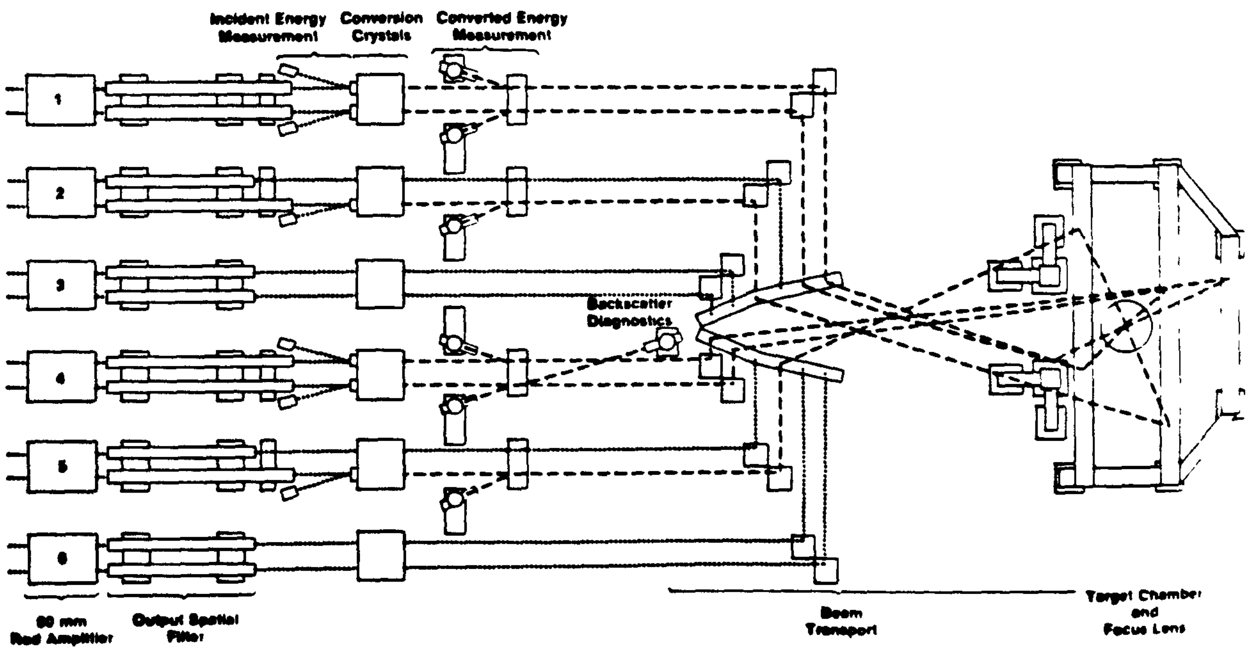


Figure 3. Schematic of overall beam layout for the OMEGA six beam, ultraviolet conversion. The beams shown in dashed lines are 351-nm beams.

Unfortunately, placing the conversion system near the target focusing lenses also presents some significiant disadvantages compared to the LAOR option, namely:

a) limited ultraviolet beam diagnostics (the blue diagnostics require retro-reflection and a double-pass through the crystals), and

b) the opto-mechanical design for such a system is more complicated and would result in higher cost and longer design/construction time than the LAOR option.

Our favorable, long-path propagation experience with OMEGA gave us confidence that UV-beam propagation from the laser bay to the target chamber should not present any serious problems. The primary trade-off was, therefore, between the diagnostic considerations and coating damage risks.

At an energy level of 90 J at 351 nm, the highest estimated flux, 1.8 J/cm^2, occurs at the blast shield. The highest flux at the mirrors at the 90-J energy level is 1.15/cm^2. In these estimates an average fill factor of 0.6 is assumed. An additional fill factor multiplier of 0.56 is used to account for local hot spots from beam defects and diffraction rings.

Coating damage measurements at LLE and elsewhere indicate that flux levels of 1.1-1.8 J/cm^2 are below the damage threshold for state-of-the-art, 351-nm AR and HR coatings.[12] For 1ω-3ω HR coatings, similar measurements show damage thresholds ranging from 1.8 to 2.6 J/cm^2. Based on these estimates and on the paramount need to have high reliability and high-accuracy beam diagnostics, it was decided to implement the LAOR option for the frequency-conversion system as shown in Fig. 3. Initially, only six of the 24 beams were converted to 351-nm operation. These six beams form a near symmetric cubic set. Additional OMEGA beams are now being converted to ultraviolet operation.

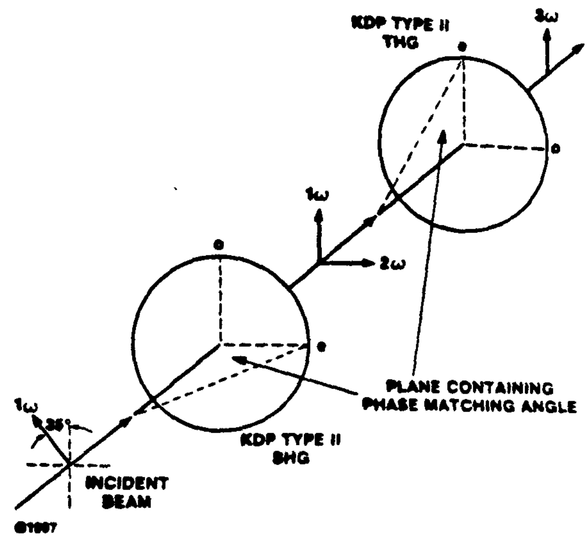
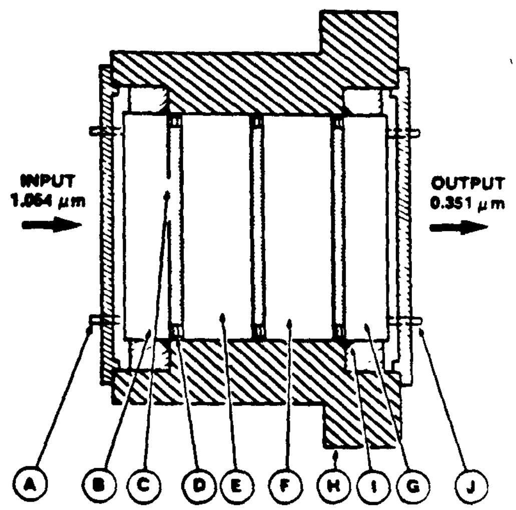


Figure 4. Polarization-mismatch, frequency-conversion scheme. The incident 1-ω radiation is polarized at 35° to the o-direction of the SHG to ensure that equal numbers of 1ω and 2ω photons emerge from the doubling stage. Both crystals are tuned about their o-direction to achieve phase-matching.

Frequency Conversion Cells

The technique used for tripling the frequency of the OMEGA beams is based on the "polarization-mismatch" scheme[6,7] shown in Fig. 4. Both the KDP second-harmonic generator (SHG) and the KDP third-harmonic generator (THG) are type-II cut, such that the z-crystallographic axis (the crystal-optic axis) makes an angle of approximately 59° with the polished optical surface normal of each crystal. 1-ω laser radiation, incident on the SHG, is linearly polarized at 35° to the o-direction of the doubler. Provided that the intensity of the incident laser radiation and the thickness of the SHG are appropriately matched, equal numbers of 1ω and 2ω photons emerge from the SHG, which is angle-tuned for phase matching. These photons are subsequently mixed in the THG to produce 3ω radiation. As indicated in Fig. 4, the THG is rotated with respect to the SHG by 90° about the system optical axis and must, therefore, be angle-tuned in a plane orthogonal to that used to tune the SHG. Both crystals are of the same thickness in order to ensure optimum performance.[8] The orthogonality of the SHG and THG crystals permits the design of a single frequency-conversion cell containing both crystals.[10] Angle tuning for proper phase matching is then accomplished in a standard gimbal mount.

The design shown in Fig. 5 incorporates the SHG and THG crystals between a common pair of fused-silica windows. A thermistor temperature sensor, mounted within the cell body in close proximity to the crystals, controls current to infrared heat lamps, which stabilizes the cell temperature to ±0.05°C. Temperature stabilization is required to decouple the cell from temperature fluctuations that occur in the OMEGA laser bay.



CODE	ITEM	DESCRIPTION
A	Swivel Pad	Solid Stop for Window
B	Input Window	Fused Silica with 1ω-3ω AR
C	Index Matching Liquid	Koolase 0.20 μm Filtered
D	Spacer	Glass, t = 150 μm
E	Type II KDP SHG	θ = 58.90°, t = 20 mm
F	Type II KDP THG	θ = 59.03°, t = 20 mm
G	Output Window	Fused Silica with 1ω-3ω AR
H	Cell Housing	Electroless Nickel Plated Aluminum 6061
I	Liquid Seal	Viton O-ring 75 Durometer
J	Spring Plunger	Stainless Steel

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Figure 5 Monolithic frequency-conversion cell. The SHG and THG crystals are held between a common pair of AR-coated, fused-silica end windows. The Koolase™ index-matching liquid eliminates the six internal reflections of the cell, and all materials have been chosen for their chemical compatibility with this liquid. Liquid-layer thicknesses are maintained at 150 μm by glass spacers.

One obvious advantage of the monolithic cell design, when compared with separate SHG and THG designs, is that it requires fewer optical elements and AR-coated surfaces. In addition, we have chosen to make the input and output windows identical to simplify spare-parts inventory. It is also convenient to use a single liquid (Koolase™) for index matching of all internal surfaces.

The clear aperture of the OMEGA cells is 20 cm and the crystal thickness was chosen to be 16 mm to optimize conversion at an incident-beam flux level of 0.5 to 1.0 GW/cm^2.

To date, the six OMEGA assemblies have been subjected to more than 100 shots each with peak-output, at 351 nm, of 84 J per beam. No significant degradation has been observed on any of the OMEGA assemblies.

Beam Diagnostics

The OMEGA beam diagnostic system is shown schematically in Fig. 6. All diagnostic beams are generated by reflection from near-normal-incidence, uncoated beam splitters.

The beam energy in all three wavelengths (1054, 527, and 351 nm) is measured by means of photodiodes deployed on a large integrating sphere which samples the output beam.

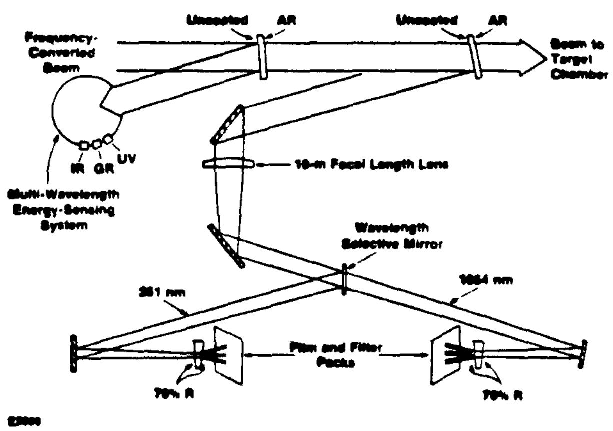

Figure 6. OMEGA Beam diagnostic system

To measure the equivalent-target-plane energy distribution of the 351 nm and compare it to the 1054 nm, we constructed the system shown schematically on Fig. 6. This system makes use of a 10-m-focal-length lens to produce images of both the 351-nm and 1054-nm light at various positions along the focal axis.

OMEGA 351-nm Performance

Measurements of the 351-nm conversion of OMEGA were carried out for over two-hundred shots. The system (1054 nm) pulse-width for the majority of these shots was held at 769 ± 38 ps (FWHM). A compilation of some of the single-beam data is shown in Fig. 7. MIXER-code[6] predictions of the beam performance is also shown in Fig. 7 for comparison. In all shots to-date, the experimentally measured 351-nm conversion agrees well with that predicted by MIXER.

A full analysis of the 351-nm distribution is shown in Fig. 8.

The intensity histogram shown in Fig. 9 shows that for the particular conditions of this shot (energy - 65.2 J, pulse width ≈ 575 ps, and focus position ≈ 1600 μm from estimated focus), the mean intensity on-target is 10^{14} W/cm^2 and the peak is 1.74×10^{14} W/cm^2.

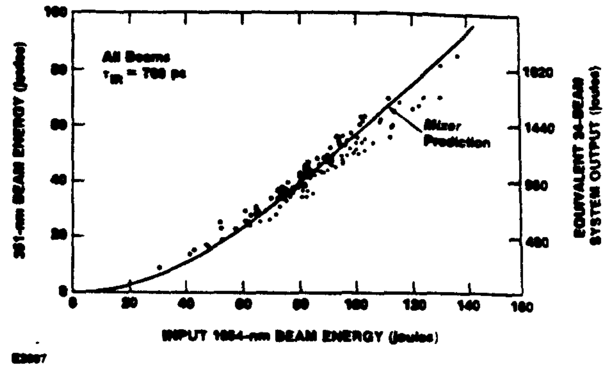

Figure 7. Summary of OMEGA 351-nm performance. All beam data is shown here for the pulse width range 769 ± 38 ps. Note the close agreement between the measured conversion and MIXER code prediction.

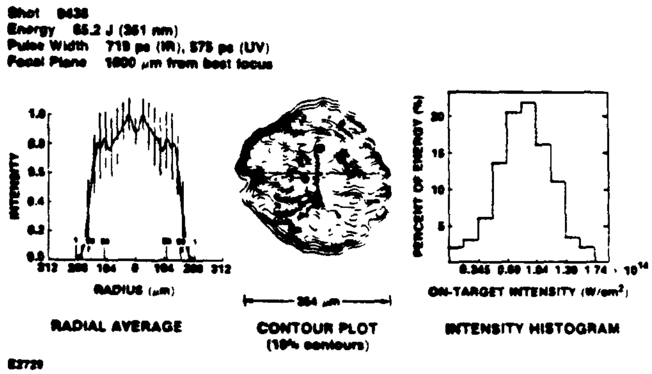

Figure 8. Analysis of equivalent target plane energy distribution for the 351-nm beam at 1600 μm from the best focus.

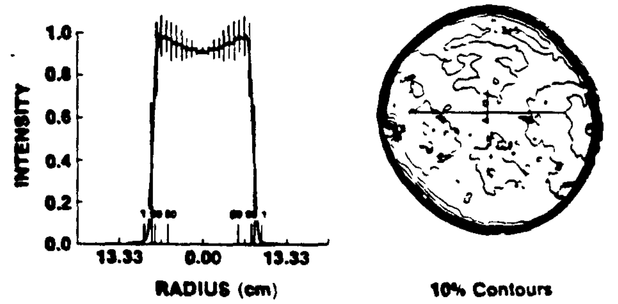

Figure 9. Near-field photograph analysis for beam 4-1 at an energy level of 58.8 J (351 nm).

The near-field, 351-nm and 1054-nm, beam distribution has also been recorded for the converted OMEGA beams. Figure 9 shows near-field data taken on the same beam as that of Fig. 8. the remarkable degree of uniformity (σ_{rms} ~ ± 8%) is a result of the high degree of alignment stability and optical quality of the OMEGA beams.

Alignment System

Early in the design deliberations for the OMEGA conversion, it was decided to maintain the 1064-nm alignment capability of the converted system and, in fact, to try to do the full-target alignment at 1064 nm. The use of auxiliary 351-nm lasers for multi-beam alignment was considered too expensive and unreliable. The transport optics were, therefore, specified to be two-wavelength capable (351 nm and 1064 nm).

The primary complications of doing 351-nm alignment with a 1064-nm beam are a) chromatic shift and chromatic aberrations in the focus lens and b) fundamental and second-harmonic rejection at the target plane.

In considering the first issue, we analyzed two competing designs for focusing optics. One of the designs was a single-element aspheric lens and the other was a two-element aspheric/aplanat. It was found that the single-element aspheric had 1.2 waves of single-pass wavefront distortion at 1064 nm compared to 0.25 waves at 351 nm. The two-element lens could produce diffraction-limited performance at both wavelengths. The consequence of the high wavefront distortion at 1064 nm is a poor focal resolution at this wavelength. We estimated that the focal resolution of the single-element lens would be ± 100 μm compared to ± 25 μm for the two-element lens. To confirm these estimates, we performed a test with a 14-cm, f/3, quartz-aspheric lens designed for 351-nm operation. We found that even though the depth of field was about 100 μm to 200 μm at 1064 nm, an operator could reproducibly focus the lens at 1064 nm to within ±12 μm of a given location. The same operator could focus a diffraction-limited lens to similar accuracy. As a result of this study, we implemented single-element aspheric lenses on OMEGA.

The second issue, 1054-nm and 532-nm rejection at the target plane was easily resolved. The blue-beam focus of the single-element aspheric is approximately 34 mm ahead of the 1054-nm focus. Under typical target conditions, the resulting intensity at 1054 nm is 10^{-3} of that at 351 nm. While solving the color separation problem, this large chromatic shift introduces some additional alignment problems, i.e., maintaining pointing stability as the lens is translated from red focus to blue focus. To solve this problem, we made use of the intrinsic high accuracy of the existing OMEGA lens holders. As shown in Fig. 10, we installed a pneumatically driven ram to provide the large-scale shift between red and blue focus; we used the existing fine adjustment to provide precision travel over 4 mm. Tests of the pointing resolution and stability and focus-position resolution and stability were carried out using x-ray imaging.

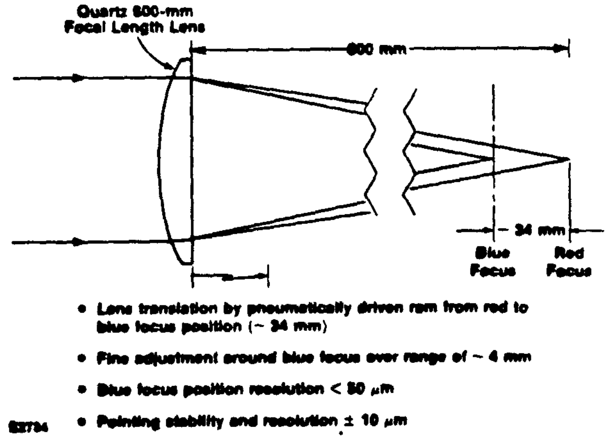

Figure 10. Characterististics of OMEGA 351-nm focusing system.

Pointing accuracy of the six blue beams was established by taking a number of shots on 600-μm-diameter spherical targets, with each beam focused on the surface of the target, and relating the regions of x-ray emission observed in the x-ray photographs to the predicted positions of the beams on the target. From a statistical analysis, a pointing accuracy ~ 10 μm is inferred. Furthermore, from analysis of photographs from a sequence of shots, the stability of this pointing accuracy was similarly ~ 10 μm. This level of accuracy is close to the minimum-step-positioning capability of the target positioner (8 μm).

Uniformity Requirements for Future Experiments

While the level of performance of the converted OMEGA beams is at the current state-of-the-art for beam uniformity, improvements will be required in order to carry out future high-density experiments. The level of performance we seek is characterized by recent 1054-nm results obtained on the GDL laser, a one-beam Nd:glass system similar to OMEGA. The equivalent-target-plane energy distribution for this system is characterized in Fig. 11.

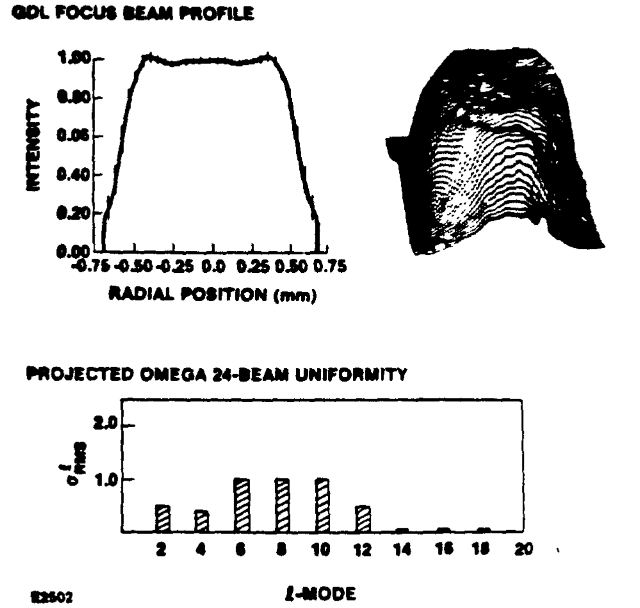

Figure 11. Equivalent-target-plane energy distribution measurement for GDL showing $\sigma_{rms} \sim \pm 5\%$. The projected uniformity for 24-beam OMEGA using this energy distribution is shown in the histogram. The energy deposition is deconvolved into spherical Legendre polynomials. The uniformity for each l-mode of the Legendre deconvolution is shown.[11]

To achieve the uniformity level shown in Fig. 11 in 351-nm beams on OMEGA will require a concentrated effort to identify and control the factors that are critical in determining the on-target characteristics of the converted beams. Some of these factors may include:

a) wave-front quality of crystal assemblies,

b) wave-front quality of transport optics, and

c) non-linear effects in the propagation of ultraviolet beams at high intensity.

An effort to identify these factors is currently underway.

IV. Summary

A large number of significant target experiments have been conducted on the OMEGA facility. Shown in Fig. 12 is a status of the laser fusion experiments conducted to date with various fusion lasers. The higher performance efficiency of a uniform illumination system such as OMEGA in direct-drive experiments is evident from Fig. 12.

Based on the 351-nm experiments conducted with both one-beam and six-beam geometries, we expect that a 24-beam OMEGA system would demonstrate compressed fuel densities of the order 100 to 200 × liquid DT density. This would be a significant milestone in the program to demonstrate the scientific feasibility of laser fusion using the direct-drive approach.

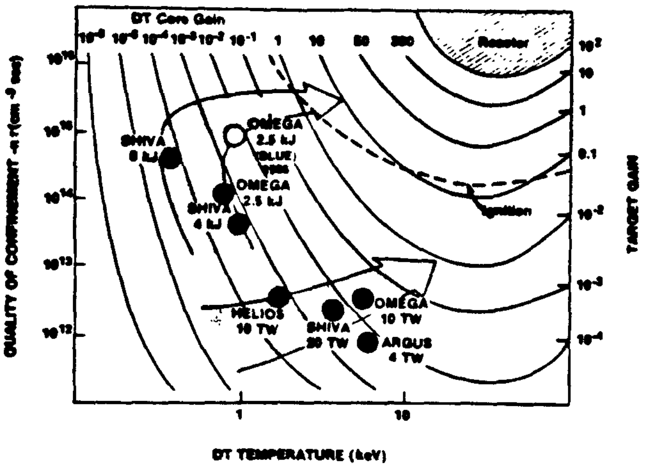

Figure 12. The status of laser-fusion research as of early 1983. The closed circles represent experimental data on the indicated lasers. The open circle represents the expected target conditions that can be achieved with the full 24-beam OMEGA system converted to 351-nm operation.

V. Acknowledgment

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