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Informal Report

MASTER

**Diffraction Measurements for
LASL's Antares Laser System**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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DIFFRACTION MEASUREMENTS FOR LASL'S ANTARES LASER SYSTEM

by

Jon E. Sollid

ABSTRACT

Beam diffraction, both in the near field and the far field, was studied to assess the effect of the 12-segmented annular exit window proposed for the Antares laser system. The near-field studies indicate that diffraction spillover effects are less than 5% and that hot spots in the aperture are not apt to exceed the design flux level of 2 J/cm^2 . The far-field investigation has shown that the segments in the annulus may be considered independently and, therefore, energy and intensity add up incoherently. Also, the total intensity distribution is well approximated by 12 times the intensity distribution in a circular aperture with the same area as a single sector.

I. NEAR FIELD

A. Description of Problem and System Layout

The 10^5 -J, 10.6- μm , 1-ns, CO_2 laser to be built at Los Alamos by 1982 for laser-induced fusion experiments will have 6 main beam lines, each of which will comprise 12 smaller beams. The six power amplifiers are annular, having an optical aperture of 230-cm o.d. and 180-cm i.d. The output aperture is determined by the energy required ($10^5 \text{ J}/6$) and by the damage threshold of

the window material (2 J/cm^2 for NaCl). Thus, the output area must be about 8300 cm^2 . The amplifier operates at 239 kPa and the $10.6\text{-}\mu\text{m}$ radiation propagates through vacuum tubes. A pressure window is consequently required. The windows must be segmented because an annular NaCl window 2 m in diameter is currently impossible to fabricate. The largest crystals that can be grown today are 40 cm in diameter and are then hot-pressed to form polycrystalline material of 46-cm diam with superior strength and stability. These pressings have an area of about 1600 cm^2 . However, the largest segment to fit into the annulus of the amplifier is an irregular trapezoidal segment of approximately 840 cm^2 . Hence, the amplifier output window must be made up of 12 such segments.

A schematic of the optical train for one of the six amplifiers is presented in Fig. 1. Section A-A, shown in Fig. 2, illustrates the geometry of the window, showing the rather large struts or separations between the window segments at the plane just in front of the beam-compressing periscope. In this plane the Fresnel number is 8890 (assuming a characteristic pane dimension of 370 mm). At Section B-B, next to a turning mirror in the beam tube, the segments are smaller due to the beam compressor and the Fresnel number is 332. At Section C-C the cross section of the beam is essentially identical to the cross section at B-B but the Fresnel number is 213.

Near-field diffraction causes some of the light to be directed out of the geometrically predicted beam paths. This loss, referred to as diffraction spill-over, must be determined; it can be minimized by the proper use of stops.

To estimate these near-field effects, digital computations were considered first. Several codes exist in the laser weapons community for estimating near-field diffraction. For example, Pratt-Whitney has a version called SOQ (System Optical Quality) and the Air Force Weapons Laboratory at Kirtland AFB has a code called OSCU, which was developed in-house. Both use Fresnel kernel propagation and allow near-field diffraction studies of modest Fresnel number. The highest Fresnel number, N , used by mid-1976

was about 40, where $N = a^2/\lambda z$, a is a characteristic dimension of the aperture, z is the range, and λ is the wavelength. Run times scale roughly as $N^2 \log_2 N$. Our smallest Fresnel numbers are about five times higher than the highest ever calculated on Air Force codes. Run times could be expected to be 60 times longer. Furthermore, as these codes are extended to regions where their applicability is questionable, the solutions still tend to provide answers a system designer would like to believe, i.e., they indicate increasing uniform phase and amplitude. Consequently, the digital approach was judged impractical and an analogue approach was adopted.

B. Experimental Measurements

An experimental mockup was built which operated in the visible and preserved the Fresnel number. Masks representing the output window after beam compression by the periscope were chemically milled in thin brass and copper foil sheets. A series of photographs were made in the near field at the Fresnel numbers 8890, 332, and 213 corresponding to the positions shown in Fig. 1. Some photographs were deliberately underexposed to display the structure due to Fresnel diffraction inside the window, and some were deliberately overexposed to display the structure due to Fresnel diffraction outside the window. The photographs, taken on Polaroid P/N 55 film, are shown in Figs. 3 through 5. Note: the higher N , the sharper the shadow and the finer, spatially, the structure. Note also that, for the smaller Fresnel numbers, the Poisson spot (the bright spot due to diffraction in the center of the shadow of an opaque disk) and the linear analogue of the Poisson spot (a bright line in the center of an opaque bar or strut) is readily apparent. Advantage of these effects may be taken for diagnostic, pointing, tracking, or alignment purposes. The highest intensity observed due to edge diffraction was 1.75 times the central average intensity in the window. The largest edge enhancement to be expected on the basis of Fresnel diffraction from a semi-infinite half-plane is 1.43. The negatives were scanned with a microdensitometer. Figure 6 shows a trace across the diameter of the

pattern obtained by overexposing at $N=213$. The negatives for the extreme cases $N=8890$ and $N=213$ were analyzed by using a video densitometer, which allows display of the information in two modes. One is an isometric rotatable and tiltable plot of $D(x,y)$, D being the optical density as perceived by the video camera as a function of position (x and y); examples are shown in Fig. 7. In the second mode up to eight colors are assigned to various density bands, which are redisplayed as pseudocolor contour plots, as shown in Fig. 8. Note the general behavior: large N , hard edge; small N , soft edge.

C. Spill-Over Measurements

To obtain some quantitative measure of the diffraction spill-over, radial photometric scans were made in two directions for the plane corresponding to $N=220$. One scan was made through the center of a window segment, $I_w(r)$, and the other, through the spoke of the window, $I_s(r)$. The results, assumed to be average radial profiles, are displayed in Fig. 9. The inside (DI) and outside (DO) diffraction were estimated numerically as

$$DI_{s,w} = \frac{\int_0^{r_i} I_{s,w}(r) r dr}{\int_0^{\infty} I_{s,w}(r) r dr} \quad (I.1)$$

$$DO_{s,w} = \frac{\int_{r_0}^{\infty} I_{s,w}(r) r dr}{\int_0^{\infty} I_{s,w}(r) r dr} \quad (I.2)$$

The total spill-over was then a weighted average of these values, the weight depending upon the angles α and β , subtended by the spoke or by the window; i.e., the inside diffraction η_i is given by

$$\eta_i = \frac{\alpha}{\alpha + \beta} DI_s + \frac{\beta}{\alpha + \beta} DI_w, \quad (I.3)$$

the outside diffraction is given by

$$\eta_0 = \frac{\alpha}{\alpha + \beta} DO_s + \frac{\beta}{\alpha + \beta} DO_w , \quad (I.4)$$

and the total diffraction is given by (I.5)

$$\eta = \eta_i + \eta_0 .$$

The result is that for $N = 230$, $\eta = 5\%$. For larger Fresnel numbers the diffraction spill-over will be less.

D. Theoretical Estimates

The effect of the struts can be adequately estimated by using the Cornu Spiral.¹ A more elaborate theoretical approach, which is a sophisticated version of Young's original theory of diffraction, is given by Keller.² Digital codes proceeding even with the most modern FFT algorithms will probably not be practical, except on the CRAY computer. The Fresnel numbers displayed in Table I have been computed by using the pane size in the window as a characteristic dimension. If coherent interaction from pane to pane is considered, then the radius of the annulus must be used as the characteristic dimension and the values below are obtained.

TABLE I

FRESNEL NUMBERS CHARACTERISTIC OF
THE ANTARES LASER SYSTEM

	<u>a = pane size</u>	<u>a = annulus radius</u>
Target mirror	213	855
Periscope	332	1 385
Turning mirror	8 890	35 740

In view of the fact that the largest Fresnel number for which computations have been made digitally is 40, this analogue approach seems very reasonable, attractive, and necessary.

II. FAR-FIELD DIFFRACTION

A. System Description and Overview

Because of the annular geometry of the amplifier and the segmented windows, the far-field pattern, or the focused spot, will have a very complicated irradiance distribution. Figure 10 illustrates the complexity introduced in the focused spot or far-field diffraction pattern due to apertures of different shapes.* A detailed calculation of these patterns would be prohibitively expensive and needlessly complex. Many gross features of the Antares far-field pattern can be predicted on the basis of very simple assumptions. For example, in the uniphasal, or coherent, case the primary pattern is composed of the diffraction pattern from an annulus which, using Babinet's principle, may be written by inspection as

$$I(r) = \left\{ \frac{2J_1(x)}{x} - \epsilon^2 \frac{J_1(\epsilon x)}{\epsilon x} \right\}^2, \quad (\text{II.1})$$

where

$$x = k a w = \frac{2\pi}{\lambda} a \frac{r}{f}, \quad (\text{II.2})$$

λ is the wavelength, a is the radius to the outside of the annulus, f is the focal length of the final focusing element, and ϵ is the obscuration ratio (the ratio of the inside radius of the annulus to the outside radius). In the limit of large arguments the first-order Bessel function may be represented as a sinusoidal function,

$$\lim_{x \rightarrow \infty} J_1(x) \rightarrow \sqrt{\frac{2}{\pi x}} \left\{ \cos\left(x - \frac{3\pi}{4}\right) \right\}. \quad (\text{II.3})$$

Substituting Eq. (II.3) in Eq. (II.1), one obtains

$$I(r) = \frac{8}{\pi x} \left\{ \cos\left(x - \frac{3\pi}{4}\right) - \sqrt{\epsilon} \cos\left(\epsilon x - \frac{3\pi}{4}\right) \right\}^2. \quad (\text{II.4})$$

* (Reproduced from Ref. 3).

The square of sums or differences of sinusoidal functions results in sum and difference frequencies, i.e., II.4 may be rewritten as

$$I(r) = \frac{8}{\pi X^3} \left(\cos^2 \left(x - \frac{3\pi}{4} \right) - \sqrt{\epsilon} \left\{ \cos(1 - \epsilon) x + \cos \left[(1 + \epsilon) x - \frac{3\pi}{2} \right] \right\} + \epsilon \cos^2 \left(\epsilon x - \frac{3\pi}{4} \right) \right) \quad (\text{II.5})$$

The primary spatial frequency of the pattern ν_0 is given by

$$\nu_0 = \frac{2\pi}{\lambda} \frac{a}{f} ; \quad (\text{II.6})$$

this is the frequency of the first term in Eq. (II.5). The second term has a frequency

$$\nu_1 = \frac{2\pi}{\lambda} \frac{a}{f} (1 - \epsilon) . \quad (\text{II.7})$$

The ratio

$$\frac{\nu_1}{\nu_0} = 1 - \epsilon \quad (\text{II.8})$$

is the ratio of "beat" fringes to primary fringe . For the compressed annulus the obscuration ratio $\epsilon = 0.66$. Therefore, $\nu_1/\nu_0 = 0.33$, and thus for every three primary fringes there is a beat fringe. Hence the pattern consists of triads of rings. Next, there is the upshifted beat at frequency ν_2 and

$$\frac{\nu_2}{\nu_0} = 1.66 . \quad (\text{II.9})$$

Therefore, for every 0.60th of a primary fringe there will be a "beat" fringe. This contributes a fine structure to the pattern. The spokes between the panes in the window contribute spikes, 12 of them, spaced 30° apart. Far out in the pattern there is another null, which is due to the chamber radius in the corners of the window. Finally, there is a coherence effect which makes the whole pattern look like rattlesnake skin. Each spike, instead of being a single spike, is composed of several adjacent spikes, each

of which is really a row of speckles whose characteristic dimension, c , is determined by the largest aperture in the system,

$$c = 1.22 \lambda \frac{a}{f} . \quad (\text{II.10})$$

Speckle may be an unfortunate word to use because to some it implies randomness. In this pattern, however, the speckle distribution is not random and is due to mutual coherence effects across the entire aperture. A labeled photograph of the far-field diffraction pattern due to the 12-segmented aperture is shown in Fig. 11.

A quantitative measurement of this pattern was needed. To this end the apparatus shown in Fig. 12 was constructed. The collimating lenses were a matched pair of achromatic doublets of 1270-mm (50-in.) focal length and 54-mm diam. The mask had an outside diameter of 29.6 mm. A pinhole of 10 μm was used as the source for the system. Its 10- μm geometrical image was much smaller than the 33- μm diffraction-limited spot size for the system.

Collimation was achieved with a shearing plate. The quality of collimation is shown by the resulting shearing interferogram made at an incident angle of 45° , shown in Fig. 13. The entire system was checked interferometrically in double pass as shown in Fig. 14. The resulting Twyman-Green interferograms for the system as a whole are shown in Fig. 15.

Quantitative measurements of the irradiance distribution in the far field were made by using a Gamma Scientific Microphotometer. This device consists of a 25- μm fiber-optic probe that can be scanned through the image plane of a microscope used to examine the image plane of the collimator pair. Typical objective magnifications were 2.5, 5.0, and 10.0. The light collected by the fiber-optic probe was measured by a photomultiplier. The linearity of the photomultiplier was measured and periodically verified during these measurements. The stable input laser signal is synchronously chopped and the photomultiplier output is measured by using phase-sensitive detection.

B. Irradiance Distribution Measurements

Irradiance distributions for a circular aperture of the same outside diameter as the mask are shown in Fig. 16 and are compared to the theoretical Airy pattern. Agreement is adequate.

The irradiance distribution for an annulus was measured next. This annulus was constructed by suspending the central obscuration on very fine 0.05-mm (0.002-in.) cross hairs. These data are plotted in Fig. 17 along the computed diffraction pattern, Eq. (II.1). Agreement is adequate. In the region of the first beat null the measurements become difficult. Note the measurements span four decades. Because the agreement between theory and measurement is adequate, confidence is established for the measured detailed structures of the 12-segmented-window pattern, which are shown in Figs. 18 and 19. Figure 18 shows the pattern along a radial section corresponding to the diffraction due to the window panes acting essentially like an annulus, whereas Fig. 19 shows the pattern along a radial section corresponding to one of the spikes due to the spoke diffraction.

C. Encircled Energy

The primary performance specification for lasers used in laser fusion experiments is the energy delivered within a particular diameter spot. As a consequence the encircled energy, defined as

$$E(d) = 2\pi \int_0^d I(r) r dr, \quad \text{II.11}$$

was measured. This was done by changing the size of the pinholes, as shown in Fig. 12.

The measured encircled energy as a function of spot radius is a rather sensitive function of wavefront quality. Even though this system was carefully designed and set up, as evidenced by Figs. 13 and 14, there is still some deviation from diffraction-limited performance. Figure 20 shows the encircled energy expected from a diffraction-limited system and next to it the measured encircled energy for an aperture the same size as the outside diameter of the annulus. There is some deviation for small pinhole sizes, probably due to the finite acceptance angle of the fiber-

optic bundle used behind the pinholes. The small pinholes diffract the light to large angles. A significant fraction of the light may be diffracted outside the acceptance cone of the fiber-optic bundle for these very small pinholes. If these measurements were to be redone a collection lens should be used behind the pinhole, which would image the mask aperture on the photodetector surface. The deviations are not significant except for very small pinhole sizes. The apparatus was deemed adequate for the determination of encircled energy over large characteristic dimensions.

Figure 21 shows, beneath the curves for the open aperture, curves that are a measure of the encircled energy from an annulus. In comparison to the circular aperture the curve for the annulus is reduced, in the limit of large collection apertures, by the ratio of aperture areas. Similarly, the 12-segmented aperture is reduced by the ratio of the areas. The theoretically encircled energy is plotted for comparison.

Below these curves is plotted the encircled energy of a single segment, which is $1/12$ th that expected from the full 12-segmented aperture. The encircled energy from a circular aperture of the same area, and a theoretical curve calculated for a square aperture of the same area, are also plotted. Note, they are essentially coincident. This leads one to the conjecture that for apertures whose boundaries are simple Jordan curves the encircled energy is essentially that of a circular aperture of the same area.

D. Effect of Real Window Material

In all the measurements the wavefront was essentially perfect and uniphasal across the window aperture. In a real situation this is unlikely to be the case. Even if the wavefront were essentially perfect across a given segment the phase could be expected to vary from segment to segment. This being the case, and provided the number of segments is sufficiently large so that the average of the cross terms is zero, the pattern of the window as a whole may be considered to be that due to the incoherent superposition of 12 single segments.

To model the effect of wavefront error, both random phase and random wedge, the segment apertures were covered with real window material. In the first instance sheet mica was used. This material has excellent wavefront quality because the sheets are very flat and very parallel. However, there are microscopic imperfections that lead to sheet separation and cause an unacceptable amount of scatter. The focused spot is largely blurred and the microscopic fine structure is destroyed, see Fig. 22. Microscope coverslips were cut into segments that fit into the window. These slips are more homogeneous than mica, and scatter, therefore, is less, but the wavefront is not as perfect. These irregularities represent mild wavefront errors, random phase, and a wedge varying from piece to piece. This setup should be a fairly reasonable simulation of an actual window. In addition, a window was made from transparent plastic Handi-Wrap. In this case the wedge is always in the same direction, but the wavefront error is rather large. The thickness and hence the phase vary uniformly across the aperture. Results of measurements with real window material in the segment apertures are shown in Figs. 23 and 21. Calculations assuming uniphasal wavefront, but of varying wavefront error, are shown with measurements in Fig. 24. Interferograms showing the window quality are presented in Fig. 25.

III. CONCLUSIONS

The major features of both the near-field and the far-field diffraction for the Antares laser system can be understood on the basis of a few simplifying assumptions.

A. Near Field

In the near field the main effect of diffraction is to cause an energy loss of about 5% in the outgoing pulse. More importantly, the diffraction may allow paths along which parasitic oscillations or prelasings may occur. These effects can be minimized with an initial system of good zero-field angle or low scatter, employing the proper field, aperture, and Lyot stops.

B. Far Field

Although the pattern from the 12-segmented window is rather complex, the encircled-energy distribution may be understood as the incoherent superposition of 12 single segments. For practical purposes this situation can be modeled by 12 circular apertures, each of the same area as a single segment. The effect of wave-front error is to degrade performance.

C. Areas of Concern

How does the fine structure affect target physics? Will the energy concentrated in the spikes, for example, affect a target detrimentally?

What is the effect of a multiline CO_2 laser pulse? Here, only the effect of a single frequency has been considered on a target plane. Next, the effect of several (e.g., six) rotational lines on a target volume must be considered. To do this in a meaningful, and not simply academic, way one must consider the effects of synchrony and target physics.

ACKNOWLEDGMENTS

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Fig. 1. Schematic of Antares optical train.

Fig. 2. Cross Sections A-A, B-B, and C-C, indicated in Fig. 1.

OVEREXPOSED

UNDEREXPOSED

Fig. 3. Near-field diffraction at Section A-A; Fresnel No. 8890.

OVEREXPOSED

UNDEREXPOSED

Fig. 4. Near-field diffraction at Section B-B; Fresnel No. 332.

OVEREXPOSED

UNDEREXPOSED

Fig. 5. Near-field diffraction at Section C-C; Fresnel No. 213.

Fig. 6. Microdensitometer trace through an overexposed negative, at Fresnel No. 213.

OVEREXPOSED
FRESNEL No =213

UNDEREXPOSED
FRESNEL No.=213

OVEREXPOSED
FRESNEL No.=8890

UNDEREXPOSED
FRESNEL No.=8890

Fig. 7. Isometric density displays from video densitometer.

**UNDER EXPOSED
FRESNEL No=213**

**OVER EXPOSED
FRESNEL No=213**

**UNDER EXPOSED
FRESNEL No=8890**

**OVER EXPOSED
FRESNEL No=8890**

Fig. 8. Pseudocolor displays from video densitometer.

Fig. 9. Photometric scans at Fresnel No. 220. Diffraction spill-over estimated to be 5%.

Fig. 10. Reproductions of photographs made by Scheiner and Hira-
yama showing far-field diffraction due to apertures of
different shape.

Fig. 10. (cont)

18.

19.

20.

21.

22.

23.

24.

Fig. 10. (cont)

28.

29.

30.

31.

32.

32.

33.

34.

35.

Fig. 10. (cont)

Fig. 11. Far-field diffraction due to 12-segmented window.

Fig. 12. Schematic of apparatus used to measure irradiance of encircled energy in the far field.

SHEARING INTERFEROGRAM SHOWING QUALITY OF COLLIMATION

Fig. 13. Schematic of shearing plate used to measure quality of collimation and the resulting shearing interferogram.

Fig. 14. Schematic of interferometric double-pass setup used to measure the total wavefront quality in the collimation system.

Fig. 15. Interferograms of the collimating system.

Fig. 16. Far-field irradiance distribution from a circular aperture, measured and calculated.

Fig. 17. Far-field irradiance distribution from an annulus, measured and calculated.

Fig. 18. Far-field irradiance distribution from a 12-segmented window; radial scan through annulus diffraction.

Fig. 19. Far-field irradiance distribution from a 12-segmented window; radial scan through spoke diffraction.

Fig. 20. Encircled energy for a circular aperture, measured and theoretical. Encircled energy for a continuous annulus and a 12-segmented annulus, measured.

Fig. 21. Encircled energy for an annulus and for a 12-segmented aperture, theoretical and measured. Encircled energy for a single segment, measured, and the encircled energy for a circular aperture of the same area, measured.

Fig. 22. Far-field diffraction from (a) a circular aperture, (b) a single segment with and without mica, (c) the 12-segmented window with and without mica.

Fig. 23. Encircled energy for a diffraction-limited circular aperture, for a circular aperture, for an annulus, a 12-segmented window, a 12-segmented window with microscope cover-slip panes, and for a 12-segmented window with Handi-Wrap panes.

Fig. 24. Comparison of encircled energy for a perfect system (calculated) and one with $\lambda/8$ rms wavefront error (calculated) to measurements made for no window material, microscope coverslips, and Handi-Wrap.

HANDI - WRAP WINDOW

HANDI - WRAP WINDOW

OPEN WINDOW

MICROSCOPE COVER SLIP
WINDOW

Fig. 25. Interferograms of the different windows.