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EXPLODING PUSHER EXPERIMENTS UTILIZING A 4π ILLUMINATION SYSTEM

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MASTER

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Efficient heating and uniform compression of microscopic laser fusion targets require highly uniform compression of the pusher and fuel. Previous experiments at the Lawrence Livermore Laboratory used two f/1 lenses of focus the 1.06 μ laser light onto the 40 to ∿ 100 μm diameter targets at ∿ 0.4 TW.[1] As expected, the resulting compression was definitely non spherical. This is seen in Fig. 1 which shows a color representation of x-ray micrographs of a series of laser fusion experiments utilizing the Janus laser operating at ∿ 0.4 TW with two f/1 focusing lenses. The absence of heating at the equatorial plane for the 80 and 100 μm diameter targets is consistent with the existence of inhibited thermal conduction by electrons.[2] The 60 μm ball shows that the laser radiation is beginning the heat the equatorial region, making the implosion more symmetric. However, it is not until we get to the 40 μm target that the incident intensity (W/cm^2) is sufficient to make the scale length for the absorption region sufficiently long to allow thermal conduction to carry the energy all the way around the glass shell.

In order to ensure more uniform illumination and heating of spherical targets - (independent of the laser intensity) a spherical illumination system was implemented for use with the Janus laser.[3,4,5] As is shown in Fig. 2 it consists of f/.47 doublet lenses and eccentricity 1/3 elliposidal mirrors, and is essentially a modified version of the system designed by C. E. Thomas[6] and used by KMSF for laser fusion experiments[7]. With the system in best focus, i.e. with the two foci from the ellipsoidal mirrors coincident with the center of the target, the marginal rays have a theoretical half-angle of 81.4°

(Fig. 2). In this configuration, the rays are all at normal incidence for an unabberated beam and ideal optics. The total illumination coverage is 0.85 x 4π. In order to cover the equatorial region of the target, the two foci must be overlapped. This configuration is shown in Fig. 3, together with the calculated intensity distribution on the target surface, assuming an input intensity profile to the lens of the form $I = I_0 \exp-(r/r_0)$.[5] Maximum illumination uniformity is thus achieved at the expense of deviation from the ray normality condition. However, as absorption due to electron plasma wave resonance effects[8-11] requires non normal incidence, this trade-off is indeed advantageous for target performance. This effect will be discussed in more detail later in the paper.

EXPERIMENTS

The spherical illumination system (hereafter designated SIS) was used for a series of target experiments on the JANUS laser system. The purpose of these pilot experiments were two fold; (1) to study the increase in neutron yield over the implosion experiments using f/1 lenses[1], and (2) to study the effects of absorption and target performance as a function of illumination overlap of the SIS. The targets used were ∿ 67 μm diameter (67 ± 3) SiO_2 microspheres with a nominal wall thickness of .5 μm and filled with an equimolar mixture of Deuterium and Tritium at 2 mg/cc.

Aligning the SIS with the numerous and to some extent "coupled" degrees of freedom between the 4 optical elements is an extremely time consuming and delicate operation.[5] Since a detailed description of the reality of the 4π illumination system is given in Ref. 5, only a brief summary is included here. It was found essential to align the system using interferometric techniques. A 30 μm diameter gold coated microsphere was placed in the target holder and a 1.06 CW YAG laser, colinear with the pulsed beam, was employed to make one lens/mirror combination of the SIS and the gold ball a Twyman-Green interferometer[12] (Fig. 4). The lens and gold coated ball were then manipulated to obtain the desired interference pattern on the IR vidicon (< 4 - 5 fringes). With one lens/mirror pair aligned, and the common focal point determined by the center of the ball, the opposite lens/mirror pair was made into a Twyman-Green interferometer and aligned on the ball. The gold coated ball was then removed and the actual target inserted in its place with the aid of a tele-microscope. Final alignment of the target ball was done utilizing the reflection from the glass surface. This would leave the target in the best focus condition with the marginal rays converging at an 81.5° half angle. Overfilling the target was achieved by first aligning the target to best focus and then using stepping motors to move the appropriate lens/mirror combination the required amount (typically 10, 15 or 20 μm). LVDT sensors were used to indicate the positions of the optical elements with a resolution of 1 μm.

Fig. 5 shows a typical example of a target experiment using the SIS. For this experiment the lens/mirror pairs had been moved to provide a 10 μm overlap, as indicated in Fig. 5a. The relevant target and laser parameters and thermonuclear yield are given in the accompanying table. Fig. 5b shows the time and space integrated x-ray spectrum from this target together with an x-ray spectrum from a similar target illuminated with two f/1 lenses.[1] Fig. 6 shows a color enhanced version of the x-ray microscope image (in the 2.5 keV region) together with a density scan in the vertical and horizontal direction showing the symmetry of the implosion. This is to be compared with the implosion of the 80 μm target shown in Fig. 1. Fig. 7 shows a comparison between the charge collector data from this experiment and a typical experiment using f/1 lenses for illumination.[1] The shift of the distribution function to higher energies for the SIS experiments is particularly evident in Fig. 7c. As of yet, there is no definite, satisfactory explanation for this shift to higher energies. We note only, that for the SIS, the charge collector probes being located in the gap between the two mirrors, are essentially looking down the incident beam. For the f/1 lens experiments, physical constraints limited the placement of the Faraday cups to angles $\gtrsim 20°$ away from the marginal rays, and were thus not monitoring the plasma energy directed back towards the focusing lens.

The experiment quoted in Fig. 5a, produced the largest neutron yield for this series of experiments, with the average yield being 6×10^6. Thus both the maximum and the average yield are a factor of ∿ 2.5 greater than those observed in the experiments using f/1 lenses and similar targets.[1] The simple scaling rules developed in Ref. 1 show that to first order, the neutron yield is determined by the useful fraction of the absorbed energy (see Ref. 1 for details). This simplistic concept is particularly true for targets of the same diameter, wall thickness and D-T fill. Thus since the experiments utilizing the SIS were done at virtually identical conditions to those of Ref. 1, we must expect the final D-T ion temperatures to be comparable. This is indeed also confirmed by measurement of the α-particle time-of-flight energy spectrum. The only increase in target performance will thus be due to the improved symmetry of the implosion, or to state it simply, to the fact that more of the D-T fuel gets heated to the peak ion temperature.

A series of experiments were performed where the overlap (the shift of each of the focal points of the lens/mirror combination away from the center of microshell target) was varied from 0 to 20 μm. The results are summarized in Fig. 8. The solid line is a theoretical absorption curve based on laser plasma simulation predictions.[10] The calculated fractional absorption is made up on contributions from parametric decay instabilities and electron plasma wave resonance effects. The absorption due to inverse Bremsstrahlung is included, but accounts for less than 1/5 of the overall absorbed energy. The shape of the curve can qualitatively be described as follows. At best focus, the absorption is totally due to parametric decay, as resonance absorption requires non normal incidence of the focused 1.06 μ light. Our failure to observe any polarization dependence on the scattered 1.06 μ light distribution when using the SIS near "best focus" is consistent with this interpretation. As the amount of overlap increases, not only do we get more uniform illumination of the ball, but resonance absorption becomes important. For large values of the overlap, the absorption decreases simply due to the fact that part of the focused light misses the target. Although the experimental results peak at a different value for the overlap, than the theoretical curve, the overall trend is supportive of the absorption model used in the simulation.

Another confirmation that the amount of overlap can significantly affect the absorption process, the transport of energy and consequently the implosion symmetry and neutron yield, is shown in Fig. 9. Here we show the x-ray microscope images (hν ∿ 2.5 keV) for two 70 μm diameter targets. Fig. 9a shows the implosion resulting from a best focus, or no overlap, condition. The imprint of the normal incidence focused beam on the target is clearly discernable, showing the ∿ 81.5° half angle convergence angle for the marginal rays. The absence of emission from the top and bottom of the shell is consistent with the existence of electron conduction inhibition mechanisms[2] (e.g. Megagauss magnetic fields), limiting the transport of energy from the critical surface to areas not exposed by the focused beam. Fig. 9b shows the implosion resulting from a 10 μm overlap focusing condition, (i.e. each focus is 10 μm) past the target center). The improvement in illumination and compression symmetry is evident. In fact, the width of the unheated equatorial gap in Fig. 9a was used to determine the optimum overlap condition of Fig. 9b. We note that an overlap of 10 μm is ∿ twice the design best overlap based on Fig. 3a. This is caused by deviations from the assumed laser input profile and aberrations in the SIS[5].

Improvement in compression symmetry can also be achieved by increasing the incident laser intensity (W/cm^2) on the target. Fig. 10 shows two identical targets illuminated with the SIS in the best focus position. Fig. 10a shows the resulting x-ray image ($h\nu \sim 2.5$ keV) when the total incident energy was 12 joules (75 psec FWHM pulse) while Fig. 10b shows the result with 30 joules of total incident energy (again 75 psec FWHM pulse). This same effect was also observed in the experiments using f/1 lenses.[1] It seems likely that the power dependent symmetrization is due to increased electron conduction caused by shortening of the effective conduction time scale resulting both from the increased heat flux available ($Q \propto I$) and the increased temperature gradient.

SUMMARY

Experiments have been performed on the Janus laser with a spherical illumination system producing very nearly uniform energy deposition on microscopic laser fusion targets. The target performance as measured by the thermonuclear reaction yield was increased by a factor of 2.5 over experiments performed with f/1 lenses.[1] Simple considerations of useful absorbed energy together with α-particle time-of-flight measurements indicate that the D-T ion temperatures were not increased over those of earlier experiments.[1] The increased neutron yield is thus to first order caused by the greater uniformity of compression achieved. Measurements of absorption as a function of focal overlap of the ellipsoidal mirrors support the hypothesis that resonance absorption plays an important role in these laser fusion experiments.

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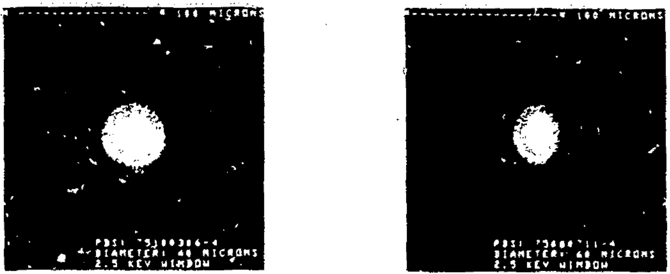
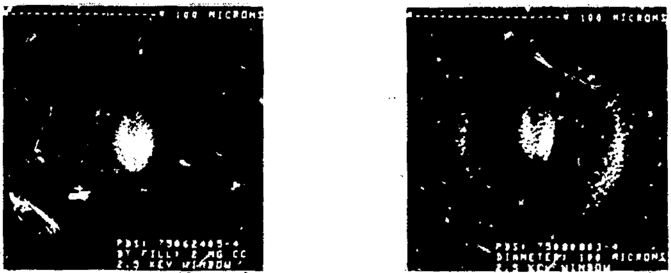
THE IMPLOSION SYMMETRY IS DEPENDENT ON INCIDENT LASER INTENSITY (W/cm²)



40-μm ball, 3.8 × 10^{16} W/cm²

60-μm ball, 1.5 × 10^{16} W/cm²



80-μm ball, 7.8 × 10^{15} W/cm²

100-μm ball, 3.8 × 10^{15} W/cm²

Figure 1

JANUS SPHERICAL ILLUMINATION SYSTEM

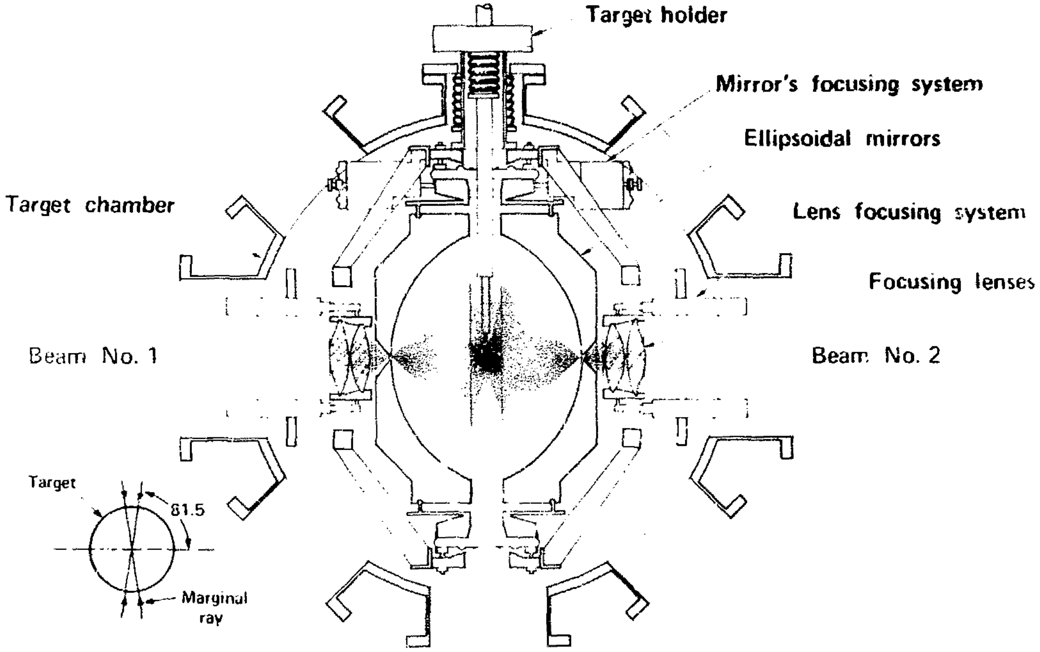
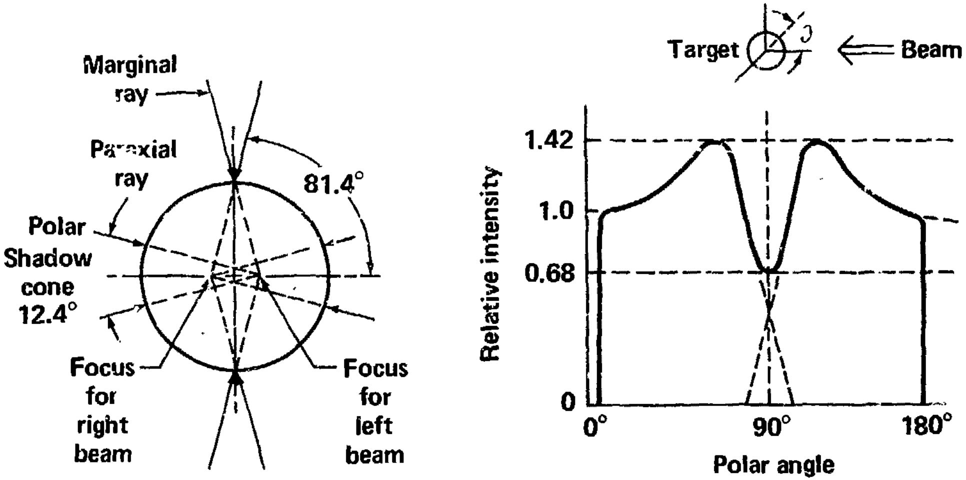


Figure 2

THE SPHERICAL ILLUMINATION SYSTEM PRODUCES A RELATIVELY UNIFORM INTENSITY DISTRIBUTION



A. Focal configuration

B. Intensity distribution

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Figure 3

THE SPHERICAL ILLUMINATION SYSTEM WAS ALIGNED INTERFEROMETRICALLY

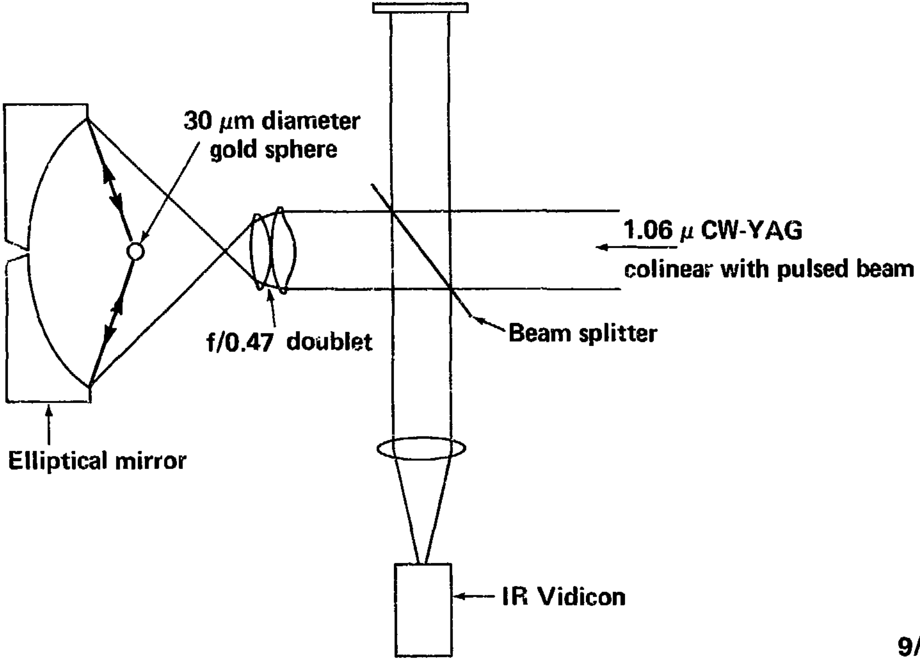

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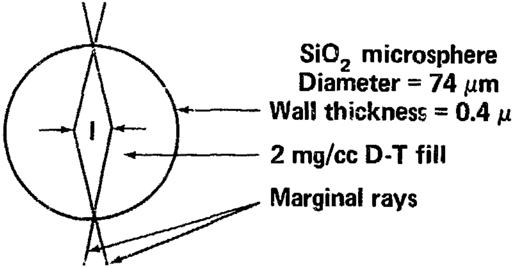
Figure 4

SYMMETRICAL IRRADIATION EXPERIMENT

Shot #76030507



Focal point overlap I = 20 μm

28.5 Joules on target ~100 psec FWHM Gaussian

8.0 Joules absorbed by optical energy balance

$(1.5 \pm 0.2) \times 10^7$ thermonuclear reactions

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Figure 5a

THE X-RAY SPECTRUM FROM EXPLODING PUSHER TARGETS IS NOT SENSITIVE TO CHANGES IN ILLUMINATION SYMMETRY

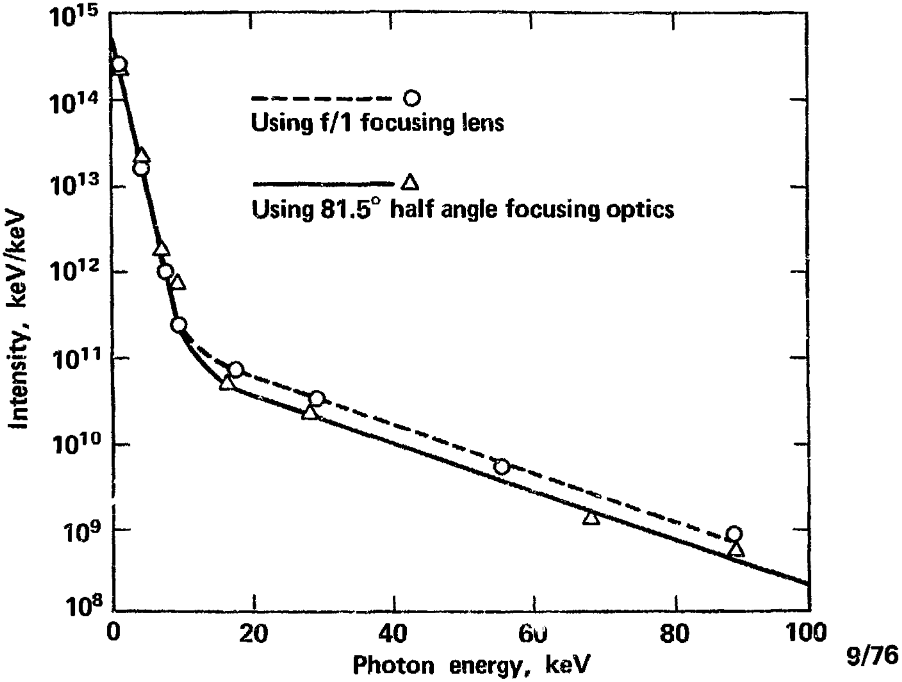


Figure 5b

A VERY UNIFORM IMPLOSION IS POSSIBLE WITH THE SPHERICAL ILLUMINATION SYSTEM

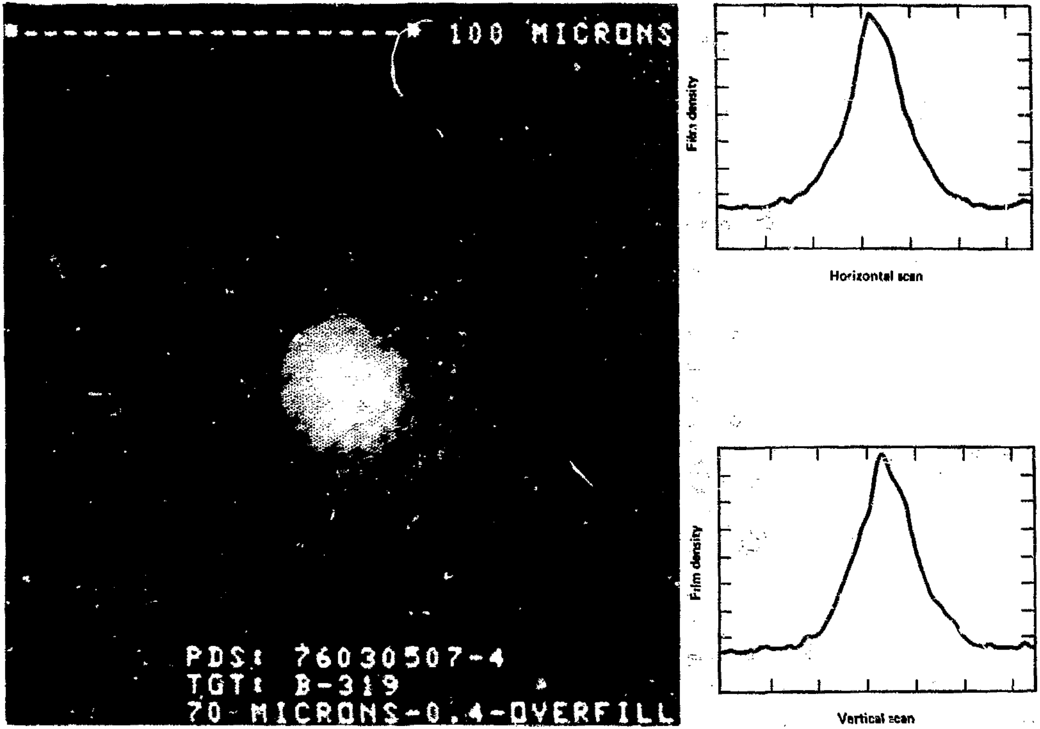
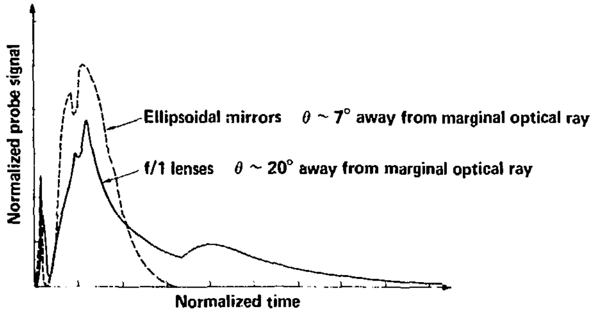


Figure 6

CHARGED PARTICLE DISTRIBUTIONS



Ion probe data for 60 μ balls

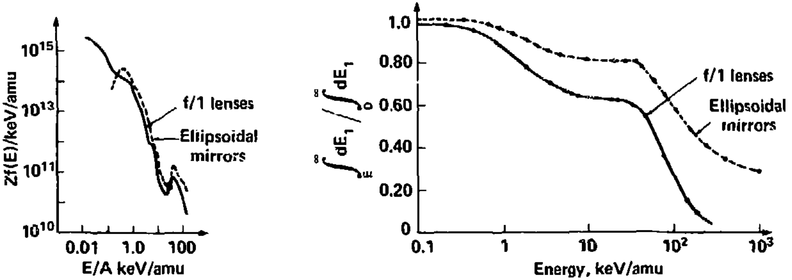


Figure 7

ABSORPTION IS SENSITIVE TO THE AMOUNT OF FOCAL OVERLAP

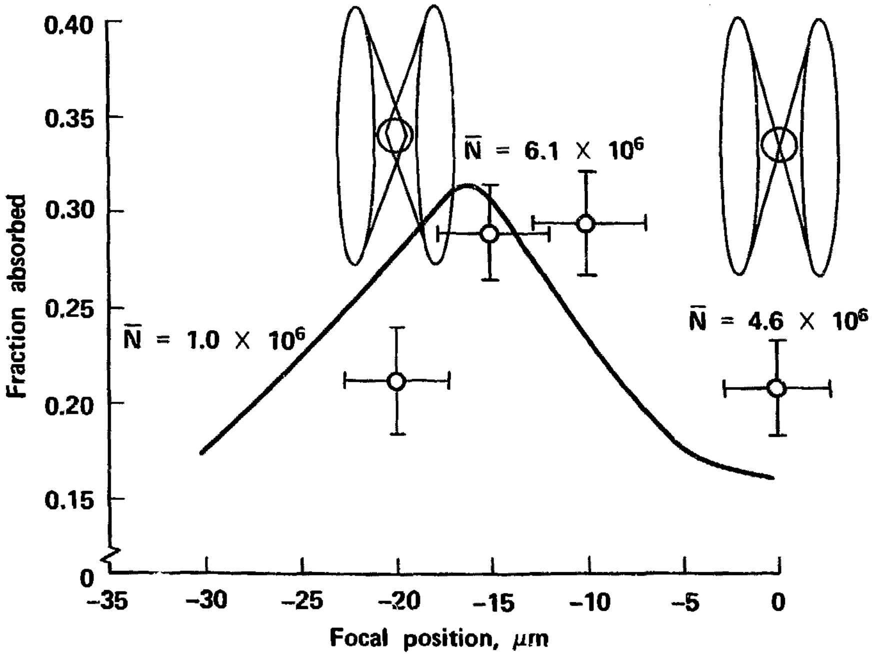
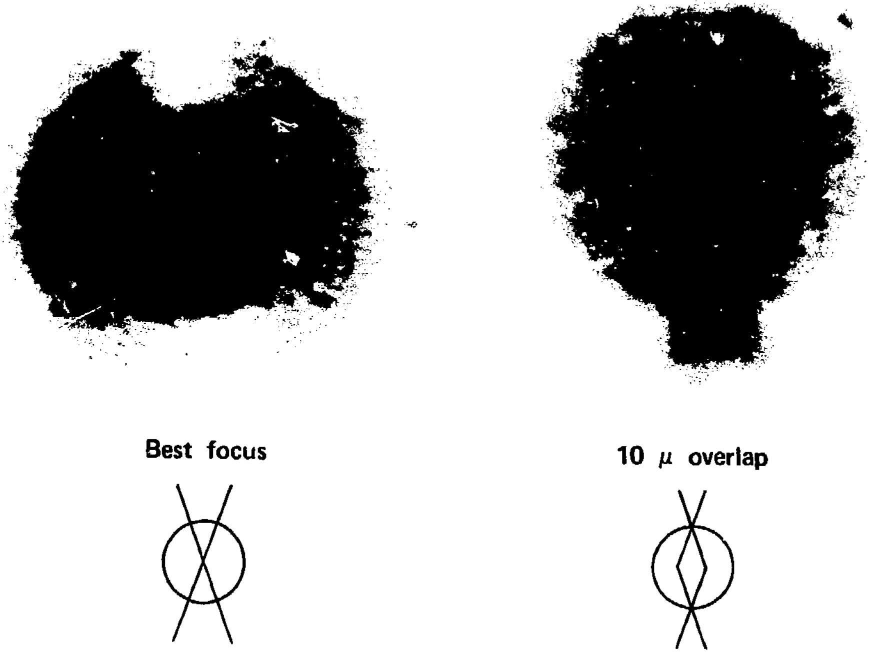


Figure 8

THE SYMMETRY OF THE IMPLOSION IS AFFECTED BY THE AMOUNT OF DEFOCUS


Best focus

10 μ overlap

Figure 9

THE IMPLOSION SYMMETRY IS AFFECTED BY INCIDENT LASER INTENSITY

65 μ diameter
0.16 TW
Best focus

65 μ diameter
0.4 TW
Best focus

Figure 10