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W. C. O'Neal, D. E. Campbell, S. S. Glaros, C. A. Hurley, M. W. Kobierecki,
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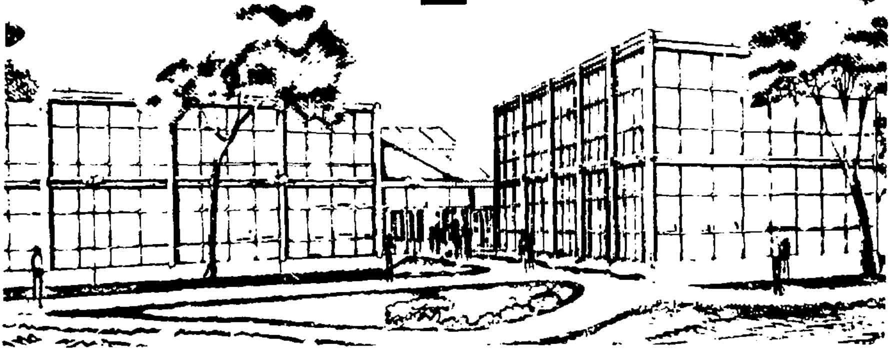

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C. B. McFann Jr., J. A. Monjes, H. G. Patton, and F. enecker Jr.

University of California
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, California 94550

ABSTRACT

Laser fusion experiments require hard vacuum in the laser beam spatial filters, target chambers and for target diagnostics instruments. Laser focusing lenses and windows, and target alignment windows must hold vacuum without optical distortion, and must be protected from target debris. The vacuum must be sufficient to prevent residual gas breakdown in focused laser light, avoid arcing at high voltage terminals, minimize contamination and melting of cryogenic targets, and prevent absorption of the target's microfusion radiation before it reaches the diagnostics instruments.

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Introduction

Laser fusion systems built at Livermore consist of Nd glass laser amplifier chains which provide from one to twenty 1.06 µm laser beams, and target chambers which contain the deuterium-tritium targets and hold the focusing lenses and target diagnostics. The systems built in the last few years are the two chain .4 TW Janus, the single chain 1 TW Cyclops, the two chain 4 TW Argus system, and the twenty chain 20 TW Shiva system shown in Figure 1. The evacuated components are target chambers shown in Figures 2 and 3 and spatial filters which reject off-axis laser light (shown in Figures 4 and 5). The spatial filters use ion pumps to maintain hard vacuum and operate in the 10^{-6} range. The target chambers use turbo pumps, cryo pumps and cold trapped mechanical roughing pumps at 10^{-4} to 10^{-6} torr. A long pump-down time may be required due to outgassing of the many diagnostics instruments, stepping motors and insulated wires placed inside the target chambers. The Shiva chamber, as shown in Figure 2, will have few instruments and no stepping motors within the vacuum and will be able to quickly pump down to the 10^{-6} torr pressure required for frozen DT targets.

Laser Induced Breakdown

In a high power focused laser beam, dielectric breakdown and light absorption can occur in initially non-ionized residual gas. The resulting plasma prevents the laser light from reaching the target. Experimental measurements[1] have been made on the breakdown thresholds for nitrogen and argon. Extrapolation of the data to the power of the LLL Shiva laser of over 10^{16} W/cm^2 shows the breakdown threshold in nitrogen to be at a pressure of about 10^{-3} torr for 10 psec long pulses. Nitrogen or water vapor would normally

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[1] "Plasmas and Laser Light", T. P. Hughes, John Wiley & Sons Publ.

be the main gas constituent in experimental target chambers. In power reactor target chambers, lithium vapor could well be the predominant gas, since a liquid lithium blanket or waterfall is envisioned as first the wall.[2] The vapor pressure of lithium is 10^{-10} torr at 450°K (the melting point) and rises to $4x10^{-4}$ torr at 700°K (the reactor operating temperature). In the 10^{-4} torr range, laser induced breakdown should not be a problem.

Laser Beam Transmission through Ionized Vacuum Vessel Gases

To calculate the order-of-magnitude maximum tolerable pressure for minimum beam absorption in ionized gas by inverse bremsstrahlung, we assume the gas in the target chamber is singly ionized, as in a glow discharge, giving one free electron for each atom in the vessel. Analysis leads to the following expression for fractional transmission of a laser beam through ionized gas:[3]

$$T_f = e^{-.039P^2 \ell}$$

where

P = pressure in torr
ℓ = distance in cm

Figure 4 is a plot of the pressure and pathlength versus light transmission. This calculation applies only to singly ionized air, which is a possible occurrence in a focused high power laser beam in a low rep-rate laser-fusion target chamber with high voltage diagnostics terminals. Plasma from previous shots in a high rep-rate laser-fusion power reactor can also provide absorbing electrons. Figure 6 shows that even in a gas discharge a high fraction of the beam would be transmitted at 10^{-2} torr. However, arc-over of high voltage diagnostics terminals could occur at this pressure.

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[2] J. Maniscalco, W. R. Meier, Transactions of the American Nuclear Soc., Vol. 26, p. 62.

[3] Jon Larsen, LLL, private communication, April 15, 1977.

Below a pressure of about 10^{-3} torr, there is no discharge (due to the low conductivity), and therefore low electron density of the gas. Target chambers utilizing high voltage diagnostics instruments within the vacuum must operate at no more than about 10^{-3} torr.

Spatial Filters

Spatial filters are used to smooth beam-profile ripples caused by nonlinear effects induced by the high power laser beams. There are about 100 such devices in the Shiva laser from 1-4 meters long and up to 300 mm in diameter as shown in Figures 4 and 5. The filter consists of an f/10 lens (which focuses the low power beam to a point about 130 μm diameter), a 500 μm diameter diamond pinhole at the focal point and another f/10 lens to recollimate the beam. The lenses are vacuum barriers at each end of an evacuated stainless steel tube which holds the adjustable pinhole. From the standpoint of laser breakdown of the gas at the focal point, the pressure required in the spatial filter, like that in the target chamber, must be less than 10^{-3} torr. However, hot material evaporated from the pinhole when it is filtering the high power beam could cause premature breakdown of the gas which would absorb or reflect the focused beam.

Also, since there are optical surfaces which must not be contaminated, a clean vacuum system is needed. To solve these problems, the spatial filters are pumped to 10^{-6} torr or less with individual ion pumps on each assembly.

Vacuum and Temperature Effects on Frozen DT Targets

In order to achieve higher compression and yield in laser imploded targets with the same laser power, frozen Deuterium Tritium targets will be used. The target chambers can be 1 to 4 meters in diameter, are generally held at room temperature and the vacuum can be maintained at from 10^{-4} to 10^{-6} torr. To improve the vacuum to 10^{-7} torr requires higher capacity pumping systems and fewer or cleaner experimental systems inside the vessel, but may be necessary for cyrogenic targets which are contaminated when they freeze out residual gas.

The five modes by which heat can be transferred to the target are radiation, residual gas conduction, conduction through the stem, self heating of the target due to the decay of the tritium, and heat from the illumination used to optically view and align the target. For an uncooled type of target, the limiting factor is the 300°K thermal radiation, and the target must be fired within about a second of its exposure to this radiation. Table I shows melt times[4] for such phenomena.

By properly shielding the target from the 300°K radiation and the vacuum contaminants, as shown in Figure 7, the target lifetime can be extended to about 50 s. In this case the limiting factor is the self-heating, and the target must be fired within 50 s of its introduction into the target chamber.

If the target is to be exposed to the target chamber environment for more than about 50 s, then some type of cooling system must be used after the target is exposed to the chamber. The most reasonable method of cooling appears to be to flow cold helium gas around the target. If this is done, the permissible exposure time can be extended to about 5 minutes.

Because of the above considerations, the system used to transport the target from the fabrication point into the target chamber must be capable of cooling and protecting the target until a very short time before the laser is fired. This system will be capable of supporting the target indefinitely and will remain in place until all of the laser systems are ready for firing.

When the preparation of the laser system is complete, all protective enclosures will be removed from the target. A short period of time will then

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[4] LLL internal report (1976 Nova CP&D).

Table I

Melt Time of Solid Frozen DT Targets, Uncooled

Phenomena	Equation	Time to Melt
300°K radiation from chamber wall	$\sigma A_T E_T (t_W^4 - t_T^4)$	1 sec
Residual gas conduction @ 10^{-6} torr	$A_T \alpha \frac{\gamma+1}{\gamma-1} \left(\frac{R}{8\pi M t}\right)^{1/2} P_g (t_W - t_T)$	$\sim$ 10 sec
Conduction through target stem	$\frac{k}{\ell} (t_s - t_T)$	$\sim$ 50 sec
Self heating	$W_T \rho V \bar{q}$	$\sim$ 50 sec
Target illumination (strobed)	$P d A_T$	> 100 sec

σ ≡ Stefan-Boltzman constant
A_T ≡ Surface area of target
E_T ≡ Emmissivity of target
α ≡ Accommodation coefficient of target
M ≡ Molecular wt. of gas
t ≡ Temperature of target, wall, stem, gas
R ≡ Molar gas constant
γ ≡ CP/CV, specific heat ratio

k ≡ Conductivity of stem
ℓ ≡ Length of stem
W_T ≡ Weight fraction of tritium
ρ ≡ Density of DT
V ≡ Volume of DT
P_g ≡ Pressure of gas
d ≡ Diameter of target
$\bar{q}$ ≡ self heating rate of tritium
P ≡ illumination power

be available for the final positioning of the target and the firing of the laser.

Problems with Diagnostics Measurements

Ions and alpha particles as well as x-rays, neutrons, electrons and light are used to measure the performance of laser fusion targets. The ions are the least penetrating particles and require the best vacuum. Calculation of the transmission of silicon ions through nitrogen illustrates the vacuum level required for accurate measurements. The transmission through non-ionized nitrogen is given by:

$T = e^{-\alpha P \ell}$

α = absorption coefficient

P = fractional pressure

ℓ = distance from target to ion probe

A calculation for silicon ions at 350 keV through nitrogen ($\alpha = 12.5\ \mathrm{cm}^{-1}$) indicates that there would be sufficient transmission (98%) of ions at 10^{-2} torr. Ion absorption has not been a problem because the target chambers are operated at pressures below 10^{-4} torr.

Stresses in Glass Vacuum Barriers

The total thickness of all high-power optical elements in the laser chain must be kept to a minimum to reduce self-focusing[5] of the beam. The B integral[6] of an optical material in a high intensity beam is a measure of the self focusing effect. It is given by:

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[5] V. I. Bespalov and V. I. Talanov, JETP Lett. 3, 307 (1966).

[6] E. S. Bliss, D. R. Speck, J. F. Holzrichter, J. H. Erkkila, and A. J. Glass, Appl. Phys. Lett. 25, 448 (1974).

$$B \approx K \int_0^z I dz$$

I = intensity, GW/cm^2

K = constant containing n_2

n_2 = nonlinear index $\approx 1.24 \times 10^{-13}$ esu for BK7 glass

z = thickness of element, cm.

Using a minimum thickness focus lens as a vacuum barrier instead of a lens plus a vacuum window reduces the amount of optical material in the beam. However, surface cracks from self-focusing or ghost focusing damage can cause a sudden fracture of the lens or window, which may be hazardous to personnel and nearby equipment. Since laser performance is improved by minimizing glass thickness, a safe lower limit on thickness must be established.

The vacuum side of the lens is in tensile stress, the exact value of which can be determined by a finite element code (for lenses) and for a plane window, or thin lens, the maximum stress (at the center, simply supported edge) is given by:

$$\sigma = \frac{3W(3m+1)}{8\pi m t^2}$$ [7]

W = load, pressure x area

m = 1/Poisson ratio

t = thickness

Figure 8 shows the stress and deflection of a window as a function of the d/t ratio.

For a given tensile stress, there is a surface crack depth, "a", which will cause sudden fracture of the lens or window:

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[7] "Formulas for Stress and Strain", Roark, p. 216.

$$a = \frac{Q}{1.21\pi} \left(\frac{K_{1C}}{\sigma} \right)^2 [8]$$

Q = crack geometry and stress level parameter.
(Q=1 for low stress and long crack)

K_{1C} = plain strain fracture toughness, KSI-in$^{1/2}$ (1000 for glasses in vacuum and 500 for glasses in air[9])

σ = maximum surface stress, psi

Figure 8 shows critical (massive fracture) crack depth vs d/t ratio for windows. The equivalent d/t for a lens can be determined by dividing the diameter by the thickness at $r/r_0 \approx 0.4$.

For example, the Shiva windows and spatial filter lenses have a d/t of ∿ of 14.3. From Figure 8 the stress is ∿ 1000 psi and the critical crack depth is 8 mm. Observed[10] single shot cracks are no more than 2-3 mm deep, which gives a safety factor of ∿ 3 on crack depth (component testing is planned to confirm the crack/stress relationship). Since repeated shots can cause further damage at the crack, inspection of thin vacuum barrier optics should be performed frequently.

Stress Birefringence and Wavefront Distortion

Although the bending stress in vacuum loaded windows is symmetrical and the positive negative stress sums to nearly zero, there is some residual stress birefringence. Measurements at LLL[11] show about a 6° rotation of the plane of polarization. The polarization analyzed intensity pattern is a typical Maltese cross. When the actual high power laser beam passes through the

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[8] Fracture Toughness Testing and Its Applications, p. 256, ASTM STP 381.

[9] Personal Communication, M. E. Prado, LLL, Livermore.

[10] W. Fountain, private communication.

[11] Internal memorandum, 4/21/77, G. J. Linford.

polarizer following the spatial filter, we calculate a loss of 1% of the energy due to the phase shift of part of the beam. This is a small amount, but is still a significant loss, which is due to the vacuum load.

Interferometric tests on vacuum loaded lenses of high d/t ratios have shown wavefront distortion to be less than $\lambda/20$ at 1.06 μm. This amount is tolerable in laser fusion optics.

Summary

The problems described have been solved by conservative design of our vacuum vessels using stainless steel and the best design and fabrication techniques. The pumping systems are oilless, trapped, and have fairly sophisticated controls to prevent accidental let-up to air. Our design pressure is 10^{-5} to 10^{-7} torr, but operating pressures reach 10^{-4} due to wiring, motors and other systems placed inside the vacuum for experimental purposes. However, when we use frozen DT targets, 10^{-6} to 10^{-7} torr is necessary to avoid melting the target.

Commercial power laser fusion systems of the future will require large pumping capacity to remove the gases generated inside the hot, high repetition rate target chambers. The operating pressure may be 10^{-3} torr or higher. The calculations we have made above indicate the feasibility of a 10^{-3} torr target chamber pressure provided cryogenic targets are protected from background radiation and heating by the chamber gases.

Acknowledgements

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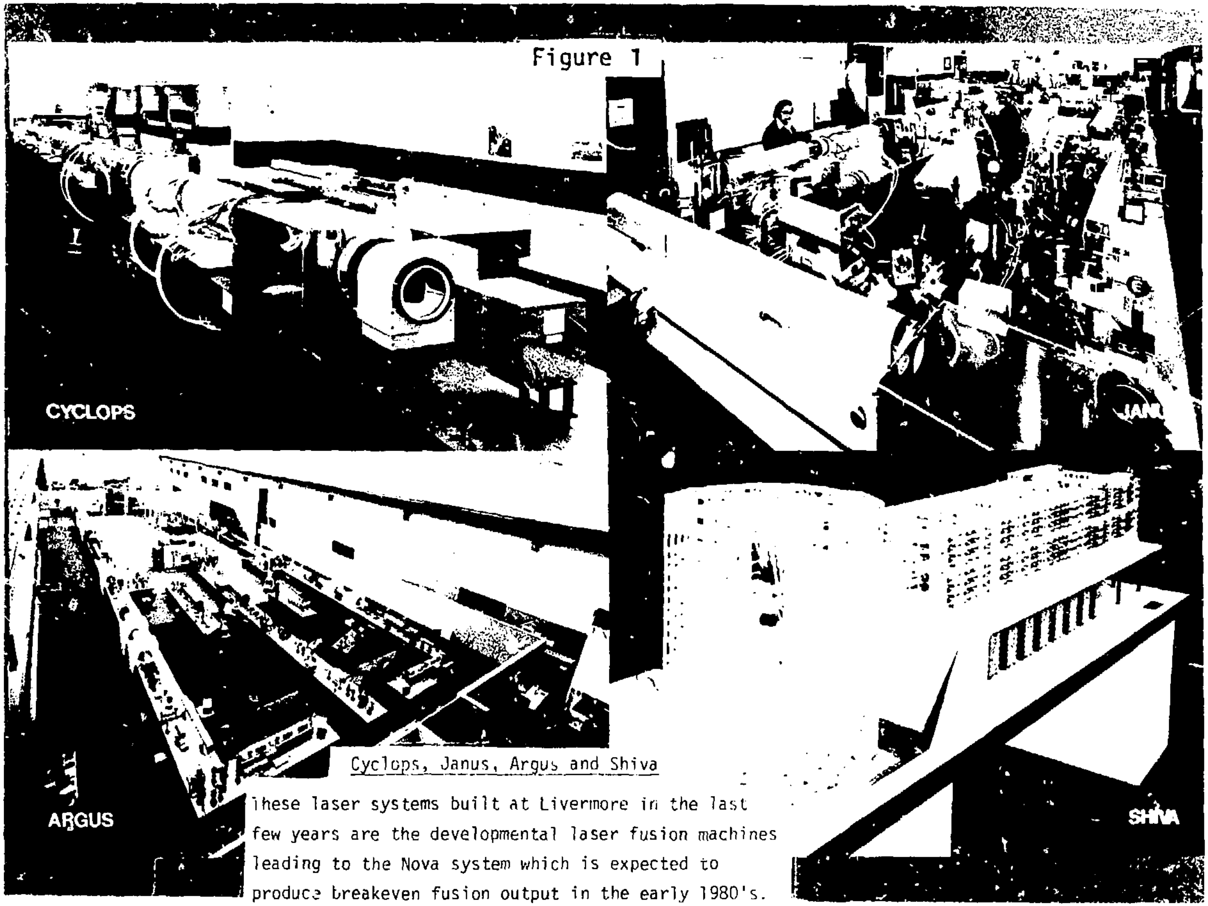


Figure 1

Cyclops, Janus, Argus and Shiva

These laser systems built at Livermore in the last few years are the developmental laser fusion machines leading to the Nova system which is expected to produce breakeven fusion output in the early 1980's.

SHIVA TARGET CHAMBER

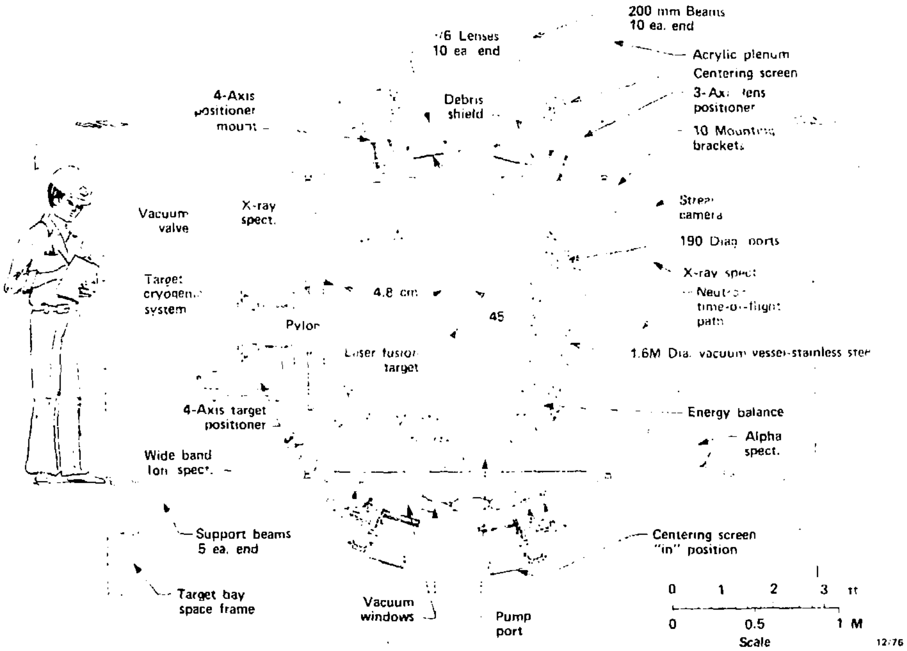


Figure 2. SHIVA TARGET CHAMBER Shiva target chamber with diagnostics instrumentation. The vacuum vessel is 1.5 m in diameter and is fabricated from 4.7 cm thick stainless steel. The focusing lenses (f/6, 220 mm diameter) are attached to the domes of the vessel. Blast shields protect the lenses from target debris. Three-axis stepper motor driven lens positioners are used to place the focus of each beam with an accuracy of ± 5 microns. Diagnostic measurements include neutron, alpha, beta, X-ray, ion and optical energy and spectra.

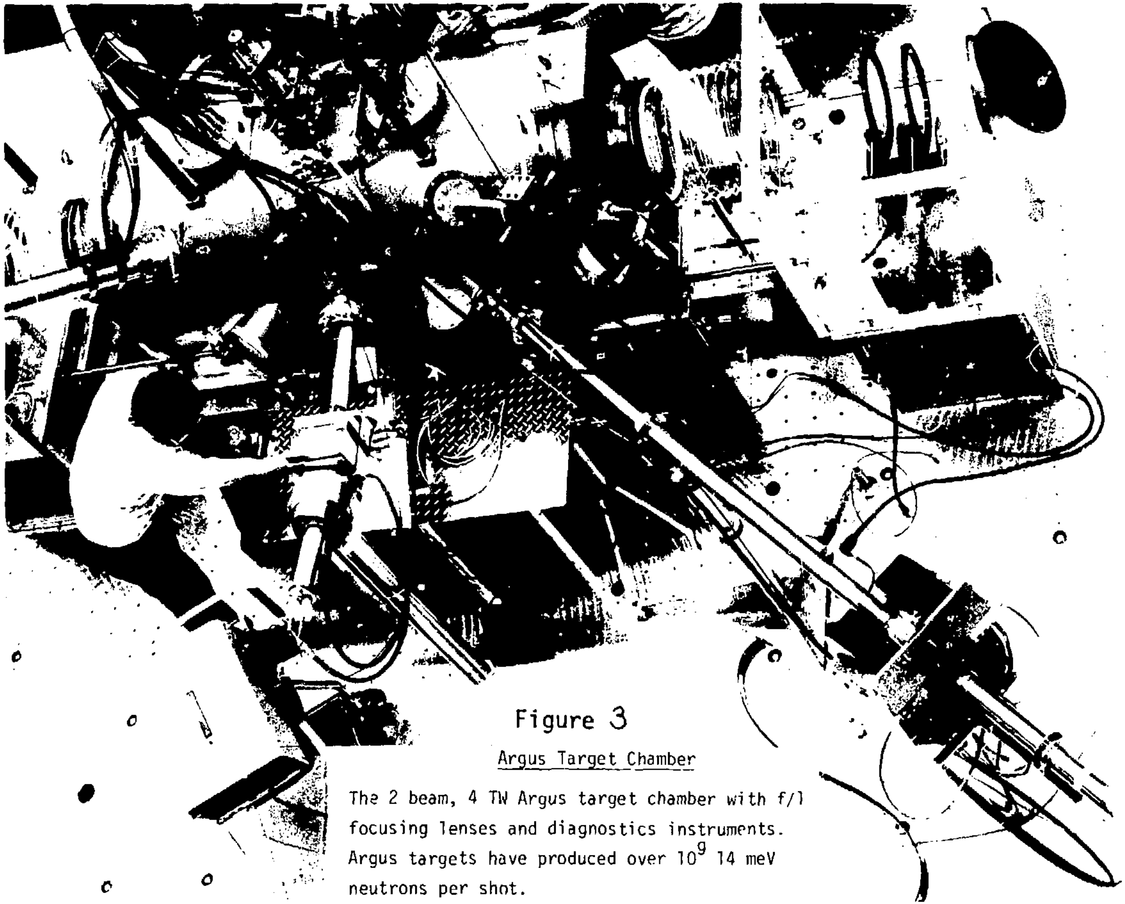


Figure 3

Argus Target Chamber

The 2 beam, 4 TW Argus target chamber with f/1 focusing lenses and diagnostics instruments. Argus targets have produced over 10^9 14 meV neutrons per shot.

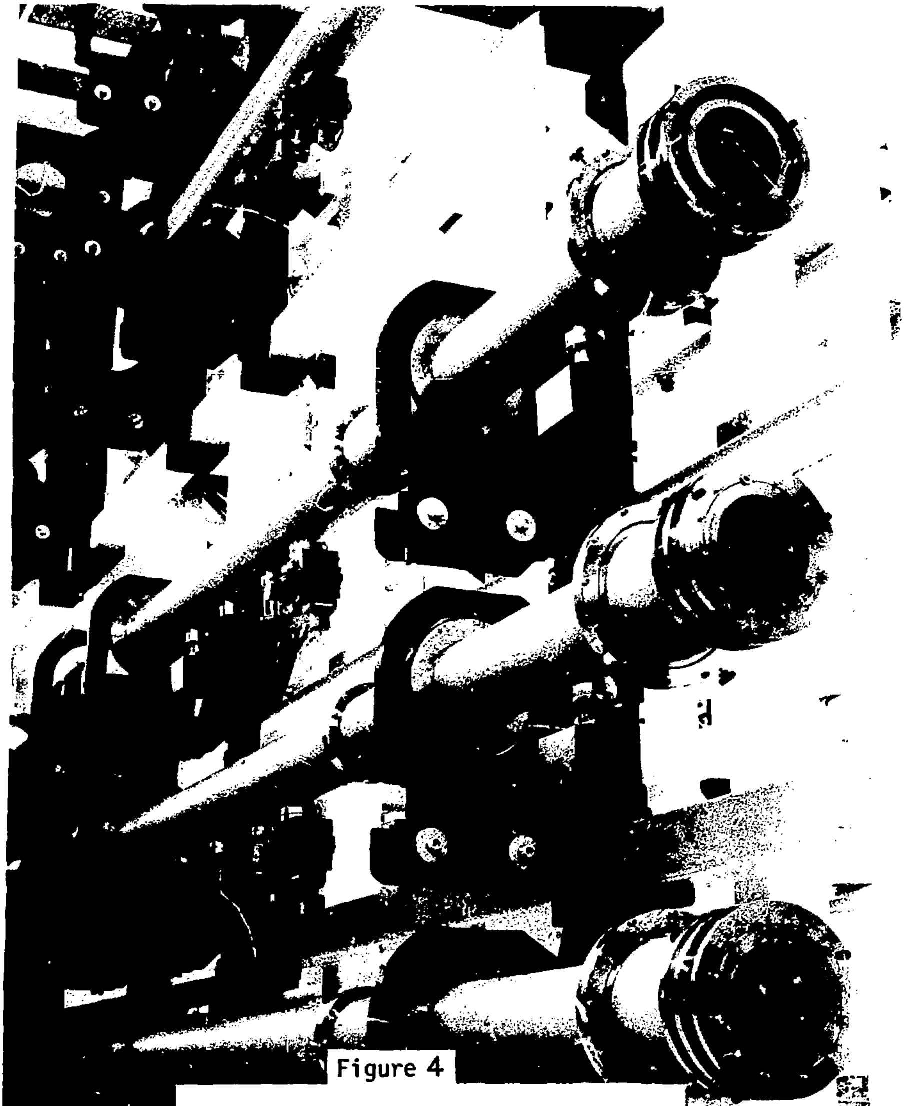
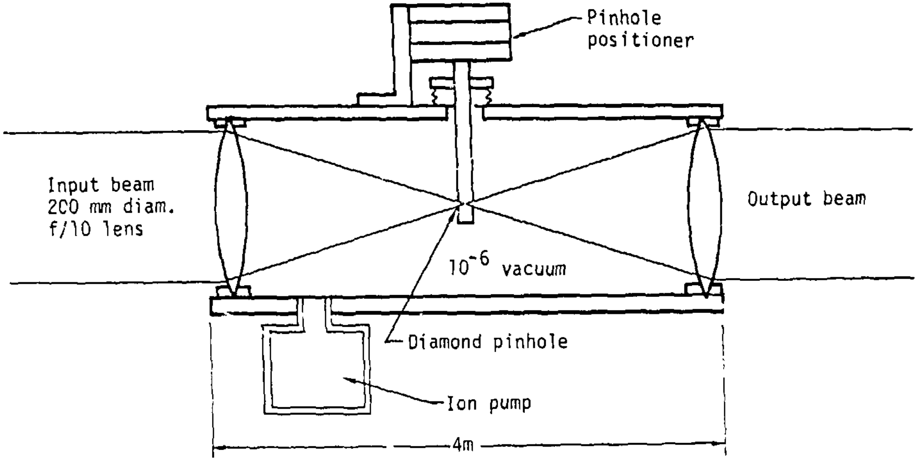


Figure 4

SPATIAL FILTERS ATTACHED TO LASER SPACEFRAME

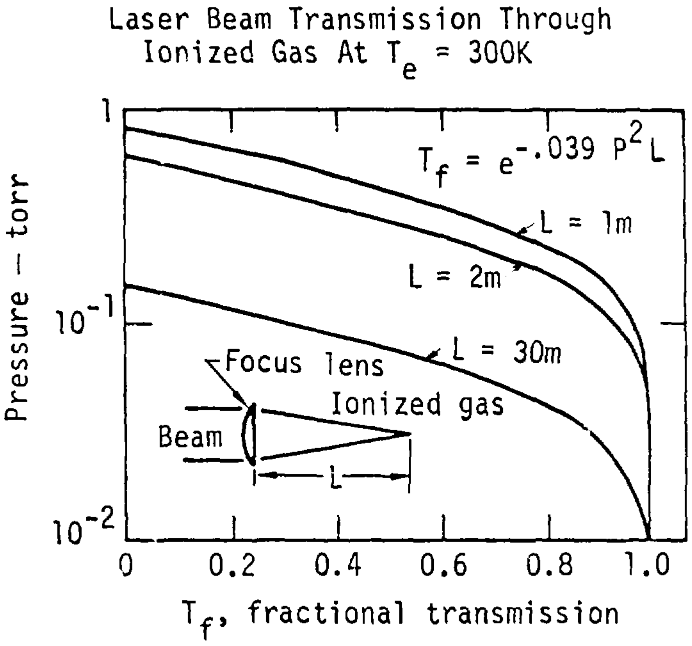
Early construction phase of Shiva showing spatial filters mounted in their support cradles and attached to the laser spaceframe. Over four-hundred components are mounted on the four vertical faces of the frame.



Spatial filter

Figure 5

In the 20 chain Shiva laser, each amplifier chain contains 4 spatial filters. Intensity and phase aberrations, caused by nonlinear optical effects induced by the high power laser beams, give rise to divergent rays which are blocked by the pinhole. With glass-damaging hot spots thus filtered out, the output beam is further amplified by the next laser head.



Laser Beam Transmission Through Ionized Gas At $T_e = 300K$

Figure 6

If the gas in the target chamber is singly ionized, as in a glow discharge at about 10^{-1} torr, transmission of a laser beam focused through a 100 cm focal length lens would be over 99%.

Frozen DT target system

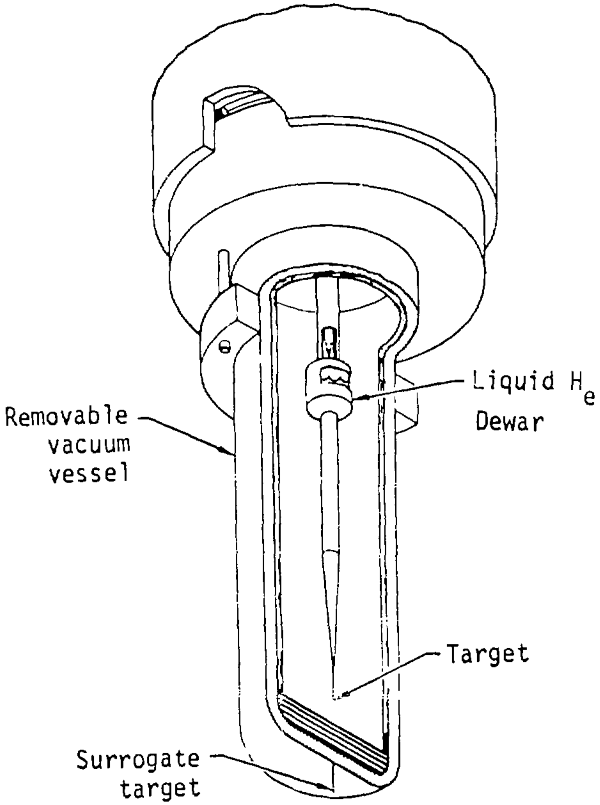
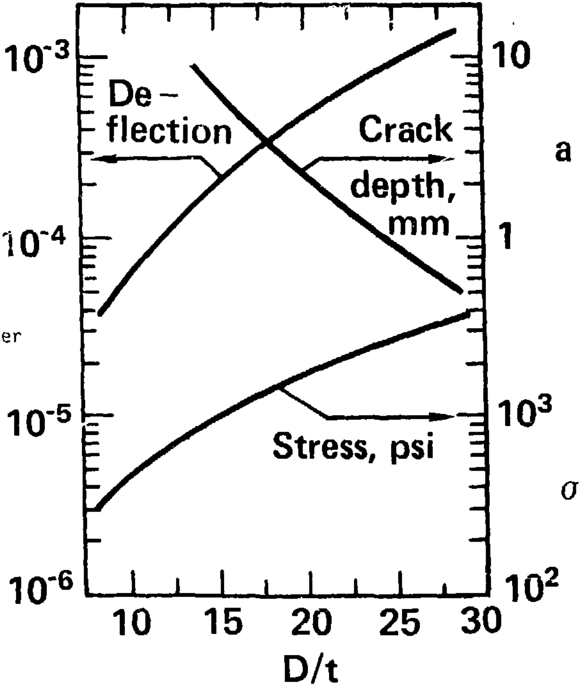


Figure 7

The removable vacuum vessel and liquid helium cooling stem keep the DT-target solidly frozen. The vacuum vessel is removed after aligning the laser on the surrogate target and moving the DT target to the firing point with the target positioner.

Figure 8

CRITICAL CRACK DEPTH, "a", STRESS, AND DEFLECTION IN A GLASS VACUUM-LOADED WINDOW



Y/D = Deflection/Diameter

$$\sigma = \frac{3W(3m+1)}{8\pi m t^2}$$