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Introduction

Laser fusion target chamber designs have evolved from simple vacuum vessels with convenient mounting flanges to complex systems optimally designed to achieve high uniformity laser illumination of a deuterium-tritium (DT) pellet. The current target chamber in design for the SHIVA laser fusion systems, for the first time, must consider large neutron, alpha, and x-ray fluences in addition to terawatts of scattered light inside the vessel.

The SHIVA laser system, which is being built at LLL, consists of a 1.06-μm master oscillator whose 100 picosecond output pulse is beam split into 20 laser amplifier chains, each outputting 1 terawatt (10^{12} watts) for a total of 20 TW with optical aberration of 1/2 wave. Before firing, the beams are automatically aimed at the target within 5 microradians and focused within 7 μm. Computer calculations predict significant thermonuclear burn will be achieved with this system.

SHIVA Target Chamber Requirements

The laser-fusion experimental target chamber serves several purposes: target injection and positioning, laser beam focusing and positioning, diagnostics instruments support, and vacuum maintenance. These functions are discussed in general below, using the SHIVA target chamber as a specific example.

The target-positioning system positions the surrogate target, a 2 mm diameter spherical mirror, for laser alignment and exchanges it with the fusion target to 1-μm accuracy. For frozen DT targets, a vacuum lock

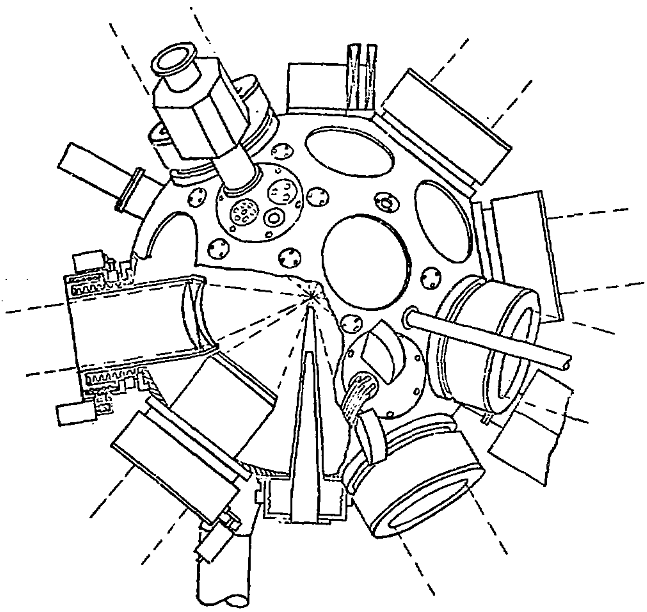

Figure 1

*Work performed under the auspices of the U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

and transfer mechanism introduces and transports the target to the firing point.

The focusing lenses are designed to project the laser beams in a precise illumination pattern on the target surface, while adding the minimum of static and dynamic aberrations to the beams.

The diagnostics instruments mounted on the target chamber are used to characterize laser beams parameters and target performance for each experiment. A tritium-gettering system absorbs the unreacted tritium from each experiment and stores it for later recovery. Figure 1 shows the 20 beam SHIVA target chamber.

The vacuum vessel and vacuum pumps provide a clean low-pressure atmosphere (10^{-7} Torr) to prevent dielectric breakdown of the gas near focus, contamination or melting of the target, lens contamination, and absorption of x-ray and ion radiation used to diagnose target performance.

Target Positioning and Control

The design requirements of the target-positioning system are that the system must center the pellet to the firing point within ± 1 μm accuracy; it must also maintain a stability of < 1 μm/min and a vibrational amplitude of less than 0.5 μm. The fine-positioning range required is ± 1 cm. The target pylon must be rigid, yet it must fit in the narrow space between the cones of focused laser beams, and not ablate from pellet fluence and reflected laser light. A system of precision ball ways, driven by remotely controlled stepping motors, will be used to drive the target pylon in x, y, and z axes. Two orthogonal vidicon tele-microscope viewing systems will be used to verify proper firing-point positioning and to view the pellet during steering to the firing point.

In addition to the micropositioning of glass and frozen DT targets, a longer range consideration of ballistically injected frozen DT pellets is necessary. The SHIVA target chamber will have space reserved for a local DT-target injection system.

For remotely fabricated frozen DT targets, the target chamber must have a vacuum lock through which the pellet can be moved to the firing point after laser alignment on the surrogate target. From the time the DT microshell has been fabricated until it is imploded, its temperature must be maintained at no more than ~17°K. This will be accomplished by a liquid-helium cooling system plumbed to the mounting base of the target stalk. The system will be located inside the pylon and will move with it during pellet transporting and positioning.

Pellet Illumination

To achieve the maximum neutron fluence predicted by LASNEX [1] code calculations, the DT pellet must be illuminated uniformly over its spherical surface to better than ± 10% during the initial energy deposition period. This can only be accomplished with high optical quality beams, and with a tailored intensity profile and pulse shape. The focused beam spots must be multiple overlapped and pointed to within a few percent of the perfect icosahedral positions.

Beam-Focusing Lens Requirements

The factors involved in lens requirements are the F/no., wavefront aberration, material, surface and internal quality, anti-reflective coating, and maintenance. For a 20-beam icosahedral irradiation system using lenses for focusing, F/1.6 lenses are the lowest F/no. that can be installed without touching each other. Illumination normality requirements drive optics toward the lowest practical F/no. Since minimizing glass thickness minimizes power loss from nonlinear optical effects, lenses must also serve as vacuum barriers, eliminating several centimeters of window glass from the beam path. The atmospheric pressure on the lenses deflects them about 12 μm, causing 1/4 wave spherical aberration, which must be pre-corrected in the fabrication of the aspheric surface. For the SHIVA lenses, it is desirable that nearly 100% of the focused light be smoothly mapped on the target surface, which is located 500 to 1500 μm in front of the focal plane.

The lenses will be focused near the center of the surrogate target during the alignment of the laser system. After alignment, the focal point will be moved axially, within 2-μm accuracy, to a point beyond the center of the target. At this focal position, the spherical wavefront will illuminate about one-fifth of the pellet surface. During the final 1000 seconds allowed for pellet placement, the lenses will maintain a positional stability of <.1 μ/hr.

SHIVA Lens Design

The SHIVA lenses are F/1.6 doublets, 330 mm diameter, 465 back focal length, aspherically figured to 1/5 wave at 0.6328-μm, including the effect of vacuum deflection. Previous laser fusion focus lenses have required 5-10 mm diameter on-axis, through holes to prevent the initiation of cracks from internally focused ghost images, which propagate and destroy the lenses. The resulting shadow on the fusion target causes intensity gradients on the target surface which locally perturb the imploding pellet, degrading the final density-temperature level. The surface curvatures and anti-reflection coatings on the SHIVA lenses are designed to minimize the intensity of internal ghost focal spots. The calculated intensity is far below the internal damage threshold, and holes are not required.

Lens-Positioning Systems

The lens positioning system is basically a focus ball screw drive mounted on a single x-y translation plate which moves on ball bearings. Table 1 lists the design parameters. Geared-down stepper motors and ball screws provide motion. The systems will be operated remote-open-loop.

Table 1

Parameter	Focus Drive	x-y Drive
Step Size	1.3 μm	0.5 μm
Focus Error, 1 σ	1 μm	1 μm
Pointing Error, 1 σ	1 μm	1 μm
Resolution	2.3 μm	1.5 μm
Range	± 10 mm	± 5 mm
Slew Rate	680 μm/sec	500
Required Torque	2.8 Nm	.34 Nm
Motor Torque	8.5 Nm	.89 Nm

[1] J. Nuckolls, J. Emmett and L. Wood, "Laser Induced Thermonuclear Fusion", Physics Today (Aug. 1973).

Diagnostics Instrumentation

The instruments that diagnose the laser beam and the laser-plasma interactions all have positioning, collimation, solid-angle-of-view, and vacuum environmental requirements. Some instruments (e.g., x-ray microscopes and pinhole cameras), require very precise alignment, whereas others with wide fields of view (e.g., PIN-diode x-ray spectrometers and 1-μm radiometers) are not critically aligned. These and other considerations determine the overall arrangement and size of the target chamber. Historically, laser target chambers have increased in diameter from 33 cm for megawatt lasers to 1 m for gigawatt lasers. Terawatt lasers require target chambers from 1.5 to 2 m in diameter and to accommodate the increased size and number of laser beams and multiple sets of diagnostics that make measurements over 4 π sr around the target. A typical set of diagnostics for the SHIVA facility is listed in Table 2.

SHIVA Target-Chamber Vacuum Vessel Design

The SHIVA target chamber is spherical, 1.6 m in diameter, with a 3.5-cm thick 304L stainless-steel wall. Thirty large (400 mm) ports are evenly distributed around the sphere: 20 laser-beam ports, 9 diagnostic ports, 2 target ports, and 1 pumpout and tritium-gettering port. In addition there are 60 small (60 mm) ports for other diagnostics and target alignment. The vacuum system evacuates the chamber to 10^{-7} Torr in 1 hour, using a combination of sorption, cryopumping, and titanium-sublimation pumping. The pressure produced will limit the buildup of contaminating elements on the target surface and will prevent attenuation of the soft x-rays, ions, and electrons used for diagnostics.

Table 2. Typical Set of Diagnostics for the SHIVA Facility

Parameter	Instrument	Number of lines of sight	Number of detectors
0.2-to-10-keV x-ray spectrum	Bent-crystal spectrometers	2	12
2-to-20-keV x-ray spectrum	Silicon PIN diode with K-edge filters	1	7
20-to-300-keV x-ray spectrum	Photomultiplier-fluor array with K-edge filters	2	4+7
1-to-10-keV time-resolved (30-ps) x-ray spectrum	X-Ray streak camera with K-edge filters	1	Film
0.5-to-3-keV x-rays	Fast x-ray diode (100 ps)	2	2
X-Ray imaging	X-Ray microscope	6	Film
Time-resolved x-ray imaging	X-Ray microscope with streak camera	2	Film
Ion spectrum and species	Thomson spectrometer	1	10
Ion angular distribution	Faraday cup	10	10
60-to-180 keV electron spectrum	Electron spectrometer	1	11
Absorbed laser energy	Photodiodes	6	20
Beam profile	Film camera	20	Film
Beam phase profile	Shear interferometer	20	Film
Space-and time-resolved beam intensity	Optical streak camera	3	Film
Reflected light spectrum from target	2.5-m McPherson spectrometer	1	Film
Neutron spectrum	Time-of-flight with photo-multiplier-plastic fluor detectors	3	6
Alpha spectrum	Time-of-flight with photo-multiplier-plastic fluor detectors	3	3

Radiation Environment for a Near-Breakeven Experiment

An estimate has been made of the surface heating of components exposed to plasma radiation. Figure 2 shows the spectral energy distribution, the surface layer temperature increase, and the neutron fluence at varying distance from the target for a 10-kJ experiment yielding 500 J of thermonuclear energy (400 J of 14-MeV neutrons and 100 J of α-particles).

The temperature increase on the surface of metals is caused primarily by the absorption of ions, x-rays, electrons, and light in a very thin (0.1-to-2-μm) layer. The 14-MeV fusion neutrons emitted by the plasma are very penetrating and do not contribute to the heating of the surface layer. Since the ions, x-rays, and light account for most of the energy and are absorbed in about 1 μm, the calculation sums all the energy (light, 5 kJ; ions, 4 kJ; x-rays, 1 kJ) and deposits the energy uniformly in a 1-μm layer of material. For glass surfaces, the light is transmitted, and only the ion and x-ray energy is absorbed. The estimated ΔT is probably accurate within a factor of 2 at some zone in the vapor/melt/solid surface layer:

$$\Delta T \approx E/4\pi r^2 \ell \rho C,$$

where E is the absorbed energy (joules), r is the distance from the target (centimeters), ℓ is the absorption thickness (centimeters), C is the specific heat (joules per gram per degree Celsius), and ρ is the density (grams per cubic centimeter).

The 2×10^{14} 14-MeV neutrons per shot (400 J of neutrons) produced by fusion reactions in the target

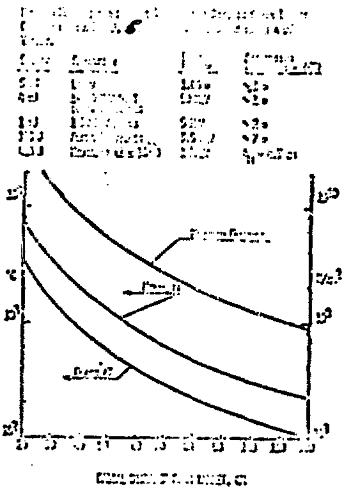

Figure 2. Neutron fluence and surface temperature rise in SHIVA target chamber from a 10-kJ, 5%-breakeven experiment using a DT target.

will not cause any heating effects, but will affect electronics and will activate materials in and around the target chamber. The dose rate (from the activated atoms) near the chamber should be less than 100 mR/hr and will drop to half this rate in less than 1 hour after the shot. Any surface material spalled or evaporated by ions, light, and x-rays will be a radioactive powder (from neutron activation), and decontamination may be required before personnel can work inside the vacuum envelope. Focus lenses will become radioactive from neutron activation of silicon and will be replaced eventually, if necessary.

The pressure increase in the target chamber caused by target vaporization and outgassing of heated surfaces is shown in Figure 3. The peak pressure of ~ 2 Torr will not produce any harmful effects in the target chamber, and the tritium-containing gas will be absorbed in the tritium-gettering system.

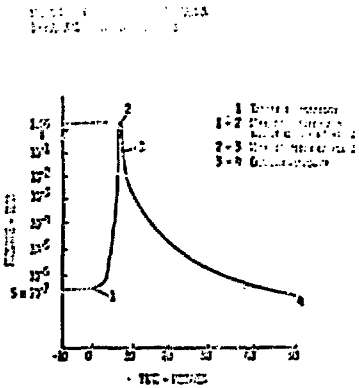

Figure 3. SHIVA target-chamber pressure after a 10-kJ, 5%-breakeven experiment.