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# HIGH RESOLUTION TIME-RESOLVED X-RAY MICROSCOPE FOR INERTIAL CONFINEMENT FUSION (ICF) TARGET DYNAMICS EXPERIMENTS*

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## Abstract

A versatile x-ray microscope diagnostic has been built to perform target dynamics experiments on the Nova Ten Beam target irradiation facility. This system is based on Wolter's axisymmetric focusing scheme. An alignment system is described which provides for both quick and accurate alignment of the x-ray optic. Results are presented showing the system resolution and accuracy of alignment. Images from target dynamics experiments are also presented.

## Introduction

The experimental study of radiation-driven target dynamics requires a high resolution time resolved x-ray imaging system. The hot plasmas generated by high power lasers such as Nova can be investigated by imaging the x rays emitted by the plasma or by backlighting and imaging the x rays that penetrate the plasma. Pinholes, cylindrical grazing-incidence double-reflection schemes [1], and zone plates [2] have all been used, but suffer from either low throughput or a complex image reconstruction process. An axisymmetric double-reflection x-ray imaging system using grazing incidence reflection off a hyperboloid and ellipsoid of revolution was first described by Wolter [3]. Compared to the Kirkpatrick-Baez cylindrical grazing incidence system, the Wolter scheme can have several orders of magnitude greater collecting solid angle and greater spatial resolution.

The annular geometry of the Wolter optic lends itself to simple alignment techniques and can be utilized to increase the versatility of the instrument. For some experiments, the depth of field can be increased at the expense of throughput by using only a small sector of the full annular collecting aperture. If two separate sectors are used with a small out-of-focus backlighting source, two images are formed from slightly different viewing directions. It is also possible to use grazing incidence x-ray mirrors to form several images with a single optic.

Development of Wolter x-ray optics for investigating laser plasmas began at LLNL in 1977 [4]. The first microscope system was fielded on the Shiva laser target chamber in 1980 [5]. A completely new system using a higher quality x-ray optic and a novel alignment scheme, has been installed on the Nova target chamber. The new alignment scheme allows the operator to easily adjust and check all aspects of alignment. This new system can accommodate a variety of x-ray streak cameras and gated x-ray detectors. Results from backlighting resolution grids show image resolution at the object plane of better than 4 μm over a field of view as large as 1 mm and positioning accuracy at the object plane better than 20 μm.

## The Wolter X-Ray Optic

The design magnification of the LLNL x-ray optics was chosen so that object features of 5 μm could be resolved using detectors with typical resolutions of 100 um. The design focal length was chosen to be long enough to limit damage to the x-ray optic from target debris yet short enough to maximize the instrument brightness and keep the dimensions of the x-ray optic and object-to-image distance manageable. In response to these criteria, several Wolter optics with a magnification of 22 and a focal length of 28 cm were built.

Characterization of some of these x-ray optics has been performed, both at LLNL [6,7] and at Atomic Weapons Research Establishment, England [8]. In general, the point spread function shows a narrow central peak, about 3 μm FWHM, but significant scatter into the wings. This x-ray scatter has been observed on other x-ray optics and is attributed to surface roughness. The properties of the x-ray optic used for this work are summarized in Table 1.

## Alignment System

In order to achieve the maximum resolution and field of view, the x-ray optic must be pointed at the center of the target, and the image must be focused and centered on the detector. This is accomplished by an alignment system consisting of two primary features: a cross hair fixed to the optical axis which can be viewed through the unobstructed center of the x-ray optic, and a high quality f/2 lens located external to the x-ray optic which forms an equivalent optical image coincident with the x-ray image. The cross hair and lens, shown in Fig. 1, are prealigned to the x-ray optic. To align the system for a target experiment, the x-ray optic is pointed at target

Table 1. Wolter optic characteristics.

Material: Ni-coated stainless steel
Collecting half-angle: 3.85°
Grazing incidence angle: 1°
X-ray reflectivity cutoff: 3.0 to 3.5 keV

| CHARACTERISTICS | FULL APERTURE |
|---|---|
| FWHM image spot diameter for a 2 μm diameter pinhole object [7] | 2.6 by 6.9 μm central peak with diffuse halo |
| Depth of field for 5 μm resolution | 75 μm |
| Field of view for 5 μm resolution | 1.0 mm diameter |
| Collection solid angle | $3.86 \times 10^{-4}$ sr |

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center by bringing the cross hair in line with the object and image points. The x-ray optic is then positioned by aligning and focusing the equivalent optical image onto the detector. Accuracy is assured because the f/2 lens has greater resolution and a much shorter depth of field than the x-ray optic. Prealignment of the equivalent lens, x-ray optic, and cross hair is performed in air using a point light source and the reflecting surfaces of the x-ray optic [8].

The manipulator for the prealigned x-ray optic, equivalent lens and cross hair is shown in Fig. 1. All of the motions required for alignment, x and y (positioning), z (focus), and phi and theta (pointing) are provided. By adjusting the lateral position of the optic instead of the image plane detector, the system can be positioned to slightly off-centered objects without the necessity of repointing the optic. A pair of translation stages powered by in-vacuum stepper motors provide zero backlash x and y motions. These stages are anchored to the structural rings of the target chamber by four 2-inch diameter aluminum support rods with adjustable clamps which provide both mechanical stability and a heat path to the chamber wall.

The phi and theta pointing adjustments pivot about the optical center of the x-ray optic/equivalent lens pair so that the pointing adjustment will not affect the alignment of the instrument. To allow a clear optical path for both the lens and x-ray optic, we designed a two-dimensional goniometric bearing. Each bearing surface is an annular section of a sphere having a radius that originates at the common optical center. The outer bearing sections are mounted on a tube and drawn together by a threaded collet that loads the bearing. The center section of the bearing remains fixed. A tube attached to the outer bearing sections extends through the x and y stages to a pair of spring-opposed linear drivers. These drivers push on the tube to provide zero backlash phi and theta adjustment. The tube supports the alignment cross hair, which remains fixed on the optic axis.

The z motion is achieved by driving the entire x-ray optic assembly, including the ball-and-socket bearing and support tube, along the z axis with a rack and pinion gear set. The x, y, and z motions are monitored by linear transducers so that any discrepancy between the actual x-ray image position and the optical image position can be measured. Systematic corrections are then made during pre-shot alignment.

During target shots, both the alignment lens and the x-ray optic must be protected from target debris. The lens is protected by a motor-driven aluminum blast shield which has a central hole to provide a clear path to the x-ray optic collecting aperture. The x-ray optic blast shield must stop high velocity particles while transmitting x rays. We have developed a blast shield consisting of a 25 μm beryllium foil supported by a 600 μm thick laminated stainless steel plate containing a single row of radial slots arranged in a circular fan. This composite is then accurately positioned over the x-ray aperture directly in front of the hyperboloidal surface.

## Alignment Illumination

A back illumination system is used for alignment of the x-ray microscope. This system, which uses an argon ion laser source (5145 Å) delivered by a fiber optic, is shown in Fig. 2. The image of a small spot of light, which is smoothed out by a rotating diffuser, is relayed to the target plane. In order to fill the f/2 collecting aperture of the alignment

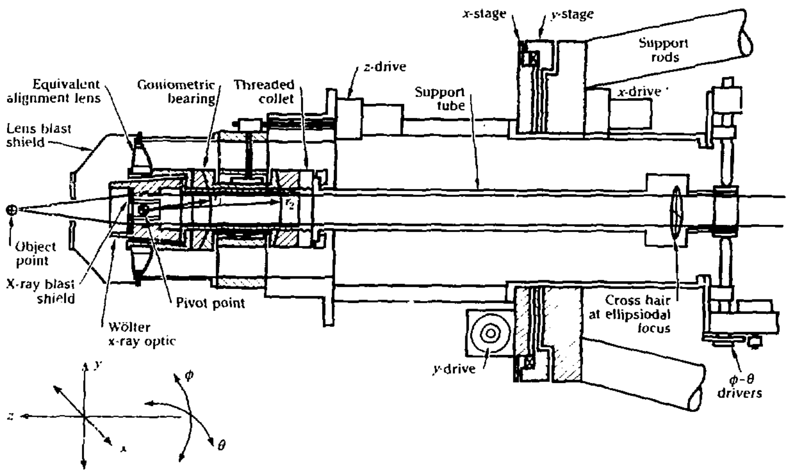


Figure 1. X-ray optic manipulator.

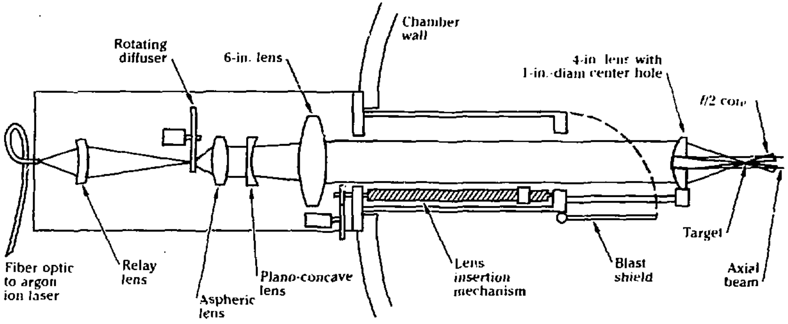


Figure 2. Back illumination system.

optic, the 4-inch diameter lens is inserted near chamber center during alignment. The aspheric and plano-concave lenses correct for spherical aberration such that the f/2 illumination spot can be made as small as 1 mm in diameter. This design conserves available light to produce the brightest possible illumination. A hole through the center of the 4-inch lens provides back illumination for viewing the alignment cross hair by allowing the slightly diverging light from the 6-inch lens to propagate down the central axis.

We also front illuminate targets with a laser beam propagating directly down the optical axis. Due to the annular collecting aperture of the alignment lens, light must be backscattered or reflected into angles between 3.5° and 7° from the optic axis. Using this front illuminator requires targets to have special alignment flags or roughened surfaces.

## System Controls

The control system for the x-ray microscope consists of four major subsystems: motor controls for the x-ray optic manipulator and blast shield components, an optical alignment system status display, target illumination system controls and status display, and vacuum system controls. All of these systems are monitored by a programmable controller that handles status signals and system interlocks. Status diagrams for the vacuum, target illumination, and optical alignment systems provide a central location for monitoring the state of all critical alignment components.

## Results

To characterize the microscope system on the Nova target irradiation facility, a series of shots were fired with a resolution grid at the focus of the x-ray optic. The resolution grid was back lit with a large area plasma. The x rays were filtered to isolate a narrow energy band used during experiments, and the image was recorded on x-ray film. A cross hair was placed on the beryllium light shield for the x-ray film as an alignment reference. Alignment was achieved by casting an optical image of the resolution grid, located at chamber center, onto the film light shield. The backlighting target was 8 mm out of focus, and the x-ray optic was closed down to two small sectors; one 15° and one 3°, oriented 180° apart. The x-ray image is shown in Fig. 3. Because the backlighter is out of focus, two regions of the grid are imaged through the two sectors of the optic. Gross features of the backlighter spot can be seen because of the increased depth of field of the small collecting apertures. It can also be seen that the contrast is better in the horizontal direction. This is indicative of the surface roughness being greater in the axial direction than the aximuthal direction of the x-ray mirrors. The resolution, defined as the 10 percent to 90 percent points at the edge of a wire was found to be 3.5 μm ± 1 μm. The maximum contrast is 72 percent in the horizontal direction and 64 percent in the vertical direction. The accuracy of the x-ray alignment can also be seen in the figure.

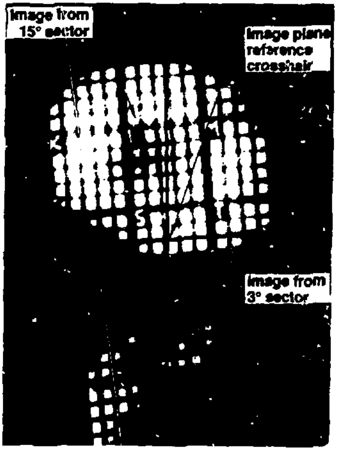


Figure 3. Back lit x-ray image of a resolution grid. The small squares have a period of 64 μm.

The small squares in the resolution grid have a period of 64 µm. During optical alignment, the center of the 5 x 5 array of squares labeled with the letter "S" was coincident with the cross hair. The x-ray image shows an error of approximately 20 µm horizontally and 30 µm vertically. These differences are reproducible within 10 µm and are due to a small error in the prealignment of the optical axes of the equivalent lens and x-ray optic.

The recorded images from two separate experiments are presented to illustrate the versatility of the instrument: one using film and a short pulse backlighting technique and one using a streak camera and self-emission from the target.

To study the Rayleigh-Taylor hydrodynamic instability associated with compressing ICF targets, a disk with periodic thickness modulations along one axis was accelerated toward the microscope by a laser-generated plasma. The disk is backlit with x rays such that the thickness variations, magnified by the instability, are recorded as bands of high and low x ray transmission, as shown in Fig. 4. Fluorosilicone was chosen for the disk because the material has good x-ray attenuation properties and exhibits relatively fast growth in the modulations. The growth rate and magnitude of the thickness variations are recorded on x-ray film with a short backlighter pulse to "freeze" the image 1.5 ns after the drive pulse. The x-rays are filtered to isolate a 100 eV band, so that the modulation amplitude can be calculated from the attenuation properties of the disk material.

Another experiment was designed to measure the convergence of an imploding target. A glass microballoon (1000 µm diameter) was filled with 25 atmospheres of DT and directly illuminated with a 1 ns pulse of 0.35 µm laser light at an irradiance of 3 x $10^{15}$ W/cm$^2$. The x ray emission from the resulting implosion was imaged into a streak camera slit and filtered for maximum transmission at 3.2 KeV. In the streaked image, shown in Fig. 5, a convergence of approximately 3:1 can be seen.

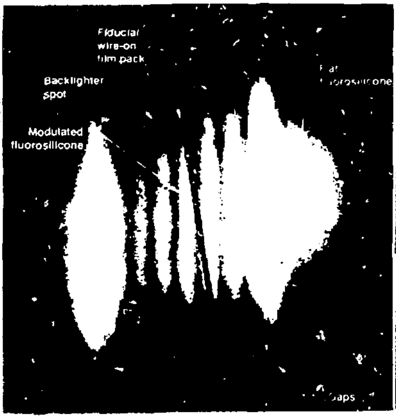


Figure 4. Rayleigh-Taylor hydrodynamic instability experiment recorded on film using flash x-ray backlighting.

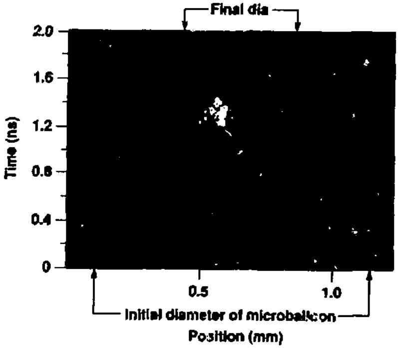


Figure 5. Implosion experiment recorded with a streak camera using x-ray emission from the target.

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