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**NORMAL-INCIDENCE MULTILAYER MIRROR
X-RAY MICROSCOPE**

**FINAL REPORT
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Summary

An x-ray multilayer mirror microscope was designed, constructed, and implemented to record images at a wavelength of $33.8 \text{ \AA}$ of laser-irradiated targets. The morphology of the $33.8 \text{ \AA}$ emission from a variety of targets was studied at the Livermore Nova laser 2-beam facility. Imaged were radiatively heated, low-density plastic and silica foams targets, x-ray laser targets, and gas-filled hohlraums. The absolute x-ray flux was determined. A two-mirror microscope and a CCD x-ray detector have been designed and constructed that will provide images with improved spatial resolution and dynamic range. The two-mirror microscope is designed to fit SIM4 on the Livermore 10-beam target chamber or any other comparably sized instrument module.

X-RAY MULTILAYER MIRROR MICROSCOPE

An x-ray microscope that images at a wavelength of $33.8 \text{ \AA}$ was designed and constructed. The microscope consists of a normal-incidence multilayer mirror that was coated to reflect x-rays with a wavelength of $33.8 \text{ \AA}$, two thin metal filters to reject longer wavelength radiation, and a film camera. The microscope was fielded at the Livermore Nova 2-beam target chamber. The

microscope vacuum chamber, attached to the Nova 2-beam chamber, is shown in Fig. 1.

The mirror substrate had a radius of curvature of 110 cm and was super-polished to an optical figure accuracy of $\lambda/10$ and surface roughness of 1 Å RMS. The mirror coating consisted of 250 alternating layers of W and B₄C. The bilayer thickness was specified so that the reflectance profile would overlap the intense C⁶⁺ Lyman-alpha transition with a wavelength of 33.736 Å. The ratio of the tungsten layer thickness to the bilayer thickness was 0.35.

The reflectance of the W/B₄C multilayer mirror was measured using synchrotron radiation. As shown in Fig. 2, for an angle of incidence of 10.2°, the peak reflectance was 1.8% at a wavelength of 33.4 Å. The calculated reflectance at an angle of incidence of 10.2° is shown by the solid curve in Fig. 2. In the calculation, the bilayer thickness was adjusted so that the peak reflectance occurred at the same wavelength as the measurement, and the layer roughness parameter was adjusted so that the peak values of the calculated and measured reflectances were comparable. The inferred bilayer thickness was 17.06 Å, and the roughness parameter was 3.4 Å. Using the same bilayer thickness and roughness parameter, the calculated reflectance peaks at a wavelength of 33.8 Å for the operating angle of incidence of 4.5° (see the dashed curve in Fig. 2) and overlaps the C⁶⁺ 33.736 Å transition.

The calculated reflectance of the W/B₄C multilayer mirror for wavelengths up to 400 Å is shown in Fig. 3(a). The feature at 66 Å results from the rapidly changing optical constants near the boron K edge. For wavelengths longer than 400 Å, the reflectance is essentially that of tungsten (the top layer). At the laser wavelength of 3510 Å, the reflectance of tungsten is 48%. It is obvious from Fig. 3(a) that the emission from the target at extreme ultraviolet

wavelengths must be blocked by filters. In addition, the intense laser light that is backscattered by the target plasma must also be blocked.

Filters were placed at the camera aperture and between the camera and the mirror. For most laser shots, the camera aperture filter consisted of 2000 Å of titanium supported by 2000 Å of Lexan ($C_{16}H_{14}O_3$). The titanium layer was relatively transmissive for wavelengths just above the L absorption edge at 27.2 Å and was opaque to visible light. The Lexan film was suitably thin and transmissive at 33.8 Å and was thick enough to provide attenuation for wavelengths in the 150-2000 Å region. For a few shots, the camera aperture filter consisted of 1000 Å of titanium, 1000 Å of aluminum, and 2000 Å of Lexan.

The metal/Lexan filter that covered the camera aperture was protected from backscattered laser light by a second filter positioned between the camera and the mirror. This filter consisted of 1800 Å of aluminum supported by a wire mesh. At the laser wavelength of 3510 Å, the aluminum/mesh filter had a reflectance of 92% and a transmittance less than 10^{-8} .

The transmittances of the aluminum/mesh and the metal/Lexan filters are shown in Fig. 3(b). The aluminum/mesh filter attenuated extreme ultraviolet radiation below the aluminum L edge at 170 Å, and the metal/Lexan filters blocked radiation above 170 Å. At a wavelength of 33.8 Å, the transmittance of the aluminum/mesh and metal/Lexan filters were approximately 40% and 30%, respectively. The overall throughput of the optical system, the product of the reflectance of the mirror and the transmittances of the two filters, was 0.2% at 33.8 Å and was many orders of magnitude smaller at longer wavelengths. The spectral purity of the recorded images was primarily defined by the reflectance profile of the multilayer mirror which had a full width at half maximum of 0.5 Å (see Fig. 2).

The 33.8 Å images were recorded on Kodak 101 or 104 roll film with grain size of 10 μm or 5 μm , respectively. The recorded images had a magnification factor of 0.3, and the spatial resolution in the target plane was limited primarily by the magnification factor and the film grain size. The film was developed in D-19 developer using the prescription of Henke et al. The images were digitized using a microdensitometer, and the optical density was converted to photon density (photons/ μm^2) using the Kodak 101 film calibration of Henke et al.

A variety of targets was irradiated at the Nova 2-beam laser facility. A total of 17 targets were imaged, and the images of 5 representative targets are shown in Figs. 4-7. The digitized image is shown at the bottom of each figure. A sketch of the target as viewed by the multilayer microscope is shown at the top of the figure, and the area covered by the digitized image is indicated by the dashed box on the sketch. The spatial scale in the target plane is indicated on the digitized image.

In Fig. 4, the target was an aluminum disk that was 5 cm in diameter and 3.2 mm thick. One laser beam was incident onto a 1.9 mm hole in the disk. The purpose of this experiment was to provide a small source with a sharp edge for the determination of the spatial resolution. The mirror viewed from the unilluminated side of the disk at an angle of 30° to the plane of the disk. The plasma streaming through the hole back-illuminated the edge of the hole, and the edge was used to determine the spatial resolution. The image was digitized with 4 μm steps and an aperture that was 10 μm square. Along a line across the edge of the hole, the optical density changed over a distance on the film of approximately 10 μm , and this corresponded to a distance of approximately 30 μm in the target plane.

The determined spatial resolution was limited by the 0.3 magnification factor of the image, the film grain size, the 10 μm microdensitometer aperture, and the spherical aberration of the concave spherical mirror operating at an angle of incidence of 4.5° . Although the spatial resolution that can be achieved by one spherical mirror is somewhat limited, the field of view is relatively large as is shown in Figs. 5-7.

Figure 5 is the image of a gas-filled hohlraum. The two ends and the bottom of the hohlraum were fabricated of thin copper sheet, and the cover of the hohlraum was 25 μm thick mylar. Two laser beams were incidence through 1000 $\text{\AA}$ thick Si_3N_4 windows in the two ends of the enclosure. The gas fill was composed of 80% pentane, 10% argon, and 10% chlorine gas. Visible in the image is emission from the plasma streaming through the window on the copper endpiece facing the mirror. Additional emission from the copper endpiece was observed in the images of two identical targets. The most interesting emission feature is the emission from the mylar region. The 25 μm thick mylar cover, under normal conditions, would be opaque to 33.8 $\text{\AA}$ radiation. The bright 33.8 $\text{\AA}$ emission from the mylar region indicates that the mylar cover was radiatively heated by the plasma within the enclosure. The mylar material either became translucent to the 33.8 $\text{\AA}$ radiation from within the enclosure or became self-emitting at a wavelength near 33.8 $\text{\AA}$ (for example, the C^{6+} Lyman-alpha transition at 33.736 $\text{\AA}$).

The image of an x-ray laser target is shown in Fig. 6. This target consisted of a yttrium strip that was 3 cm long and 1 mm wide supported by a thin plastic foil and an aluminum frame. One line-focused laser beam was incidence normal to the target. The multilayer mirror viewed the illuminated side of the target at an angle of 30° to the plane of the target. Visible in the image are emissions from the yttrium strip and the alignment mirror on the

far side of the target (right side of the image). An emission gap in the center of the yttrium strip is visible as well as a vertical clam-shaped emission feature centered on the gap. The emission gap and the vertical emission feature result from optics in the Nova laser beamline that occult and scatter the center portion of the laser beam.

Figure 7 is the image of a low-density plastic (CH) foam target that was radiatively heated by the x-ray continuum from a gold burnthrough foil. The purpose of this experiment was to determine the intensity and spatial extent of the emission from the plastic foam. One laser beam was incident from the left onto the gold foil, and the mirror viewed the unilluminated side of the foil at an angle of 30° to the plane of the foil. Within the $0.5 \text{ \AA}$ waveband centered at $33.8 \text{ \AA}$ that was defined by the reflectance profile of the multilayer coating, the emission from the radiatively heated plastic foam was as intense, although not as spatially extensive, as the emission from the gold foil. Emission from the two glass stalks that supported the gold foil and the plastic foam is also visible. Similar images were recorded of radiatively heated low-density (8 mg/cm^3) silica (SiO_2) aerogel targets.

The image shown in Fig. 7 was submitted to the Radiology Centennial Imaging Contest and won a Second Place award. This was a worldwide contest in celebration of the discovery of x-rays by Roentgen in 1895.

The absolute $33.8 \text{ \AA}$ flux was estimated from the calibration of Kodak 101 film. The film calibration was determined at a number of discrete wavelengths, and $33.06 \text{ \AA}$ was the closest wavelength to $33.8 \text{ \AA}$. The film calibration was determined for a range of optical densities from 0.2 (corresponding to a photon density of $0.34 \text{ photon}/\mu\text{m}^2$) to 1.8 ($8.07 \text{ photon}/\mu\text{m}^2$). For all of the images of laser-irradiated targets, the optical densities in the brightest part of the images were in the range of 2 to 3. Since these optical densities are beyond

the range of the calibration, we can determine a lower bound on the incident flux and can only estimate the actual flux based on the extrapolation of the calibration curve to higher optical densities.

For the linear target shown in Fig. 6, the optical density of the Kodak 101 film exceeded 1.8 over an area on the film of 5.5 mm by 1.9 mm. The average optical density over this area was 2.5. Thus the lower bound on the incident flux is 8×10^7 photons, and an estimate of the actual flux is 10^9 photons. Using the reflectance (1.8%) of the multilayer mirror and the transmittances of the two filters (40% and 30%), approximately 5×10^{11} photons were incident on the mirror. The illuminated area of the mirror was 60 cm^2 , and the fraction of the 2π solid angle subtended by the mirror was 1.7×10^{-4} . Assuming that the emission was isotropic, 3×10^{15} photons were radiated by the target within the multilayer mirror's waveband (with a full width at half maximum of $0.5 \text{ \AA}$). The spectral radiance per area of emitting surface was $2 \times 10^8 \text{ W cm}^{-2} \text{ \AA}^{-1}$. This is approximately an order of magnitude higher than the spectral radiance at a wavelength of $130 \text{ \AA}$ that was determined in previous experiments.

TWO-MIRROR X-RAY MICROSCOPE WITH CCD DETECTION

An x-ray microscope consisting of two normal-incidence multilayer mirrors was designed and constructed. The microscope was designed for a Six Inch Manipulator (SIM). A photograph of the SIM cart is shown in Fig. 8. Shown are the primary and secondary mirror mounts. The tilt and tip of the secondary mirror is controlled by two stepper motors, and the z-motion of the cart is controlled by a third stepper motor. Thus after insertion of the microscope cart in the SIM tube, the white-light image can be focused onto the CCD detector by remote control.

The CCD is housed in a differentially-pumped vacuum chamber that is designed to attach to the end of SIM4 at the Livermore 10-beam target chamber as shown in Fig. 9. A detailed schematic of the CCD chamber is shown in Fig. 10. The CCD chamber has a gate valve and differential pumping to isolate the cooled CCD from the 10-beam vacuum chamber. The CCD chamber also has a filter valve with a thin metal filter to block visible and XUV light from the target. The filter valve is opened for white-light focusing of the microscope using the stepper motors. A photograph of the CCD detector valve and pump assembly is shown in Fig. 11.

The CCD x-ray detector was built in cooperation with Goddard Space Flight Center using a backup CCD chip from the soft x-ray telescope that was flown on the Yohkoh spacecraft. The CCD has 1024x1024 pixel format with 18 μm pixel spacing. The quantum efficiency of the CCD is about 10-20% at a wavelength of 34 Å, and the CCD is also capable of recording white-light images. As shown in Fig. 12, the CCD is mounted on a cold finger and is cooled by a two-stage TEC.

The two-mirror microscope and CCD x-ray detector will be fielded at the Livermore 10-beam target chamber on SIM4. SIM4 views perpendicular to the axis of the hohlraum target at an angle of 30° below the equator of the chamber. There is about 10 feet of clear access beyond the end of SIM4 to position the CCD detector for large magnification. Initial experiments will be performed at X10 magnification resulting in a spatial resolution of 1.8 μm in the target plane.

Fig. 1. The x-ray microscope vacuum chamber at the Livermore Nova 2-beam target chamber.

FIG. 2. The measured reflectance of the W/B₄C multilayer mirror at an angle of incidence of 10.2° (solid curve with data points). The calculated reflectance is also shown for angles of incidence of 10.2° (solid curve) and 4.5° (dashed curve).

FIG. 3. (a) The calculated reflectance of the W/B₄C multilayer mirror at an angle of incidence of 4.5°. (b) The transmittances of the 1800 Å Al filter (solid curve), the 1000 Å Ti/1000 Å Al/2000 Å Lexan filter (dashed curve), and the 2000 Å Ti/2000 Å Lexan filter (dot-dashed curve).

Fig. 4. The image of an aluminum disk that was irradiated from the left by one Nova laser beam. Visible is the plasma streaming through the hole in the disk.

Fig. 5. The image of a gas-filled hohlraum that was irradiated by two Nova beams that were incident through the two Si₃N₄ windows on the ends of the hohlraum.

Fig. 6. The image of an x-ray laser target that was irradiated by one line-focused Nova laser beam,

Fig. 7. This image won a Second Place in the Radiology Centennial Imaging Contest, a worldwide contest in celebration of the discovery of x-rays by Roentgen in 1895. The image is of a gold burnthrough foil and a plastic foam cylinder. One Nova beam was incident from the left onto the gold foil, and the plastic cylinder was radiatively heated by the x-ray continuum from the gold foil. Also visible in the image are the two glass stalks that supported the gold foil and the plastic cylinder.

Fig. 8. Photograph of the x-ray microscope SIM cart. The primary and secondary mirror mounts with stepper motor control are shown.

Fig. 9. Schematic of the CCD x-ray detector assembly for attachment to the end of SIM4 on the Nova 10-beam target chamber.

Fig. 10. Detailed schematic of the CCD x-ray detector assembly showing the differential pumping and the filter valve.

Fig. 11. The differentially-pumped CCD x-ray detector assembly.

Fig. 12. The CCD x-ray detector showing the electrical feed-throughs and the cold finger.