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REP-RATED X-RAY DAMAGE AND ABLATION EXPERIMENTS FOR IFE AND ICF APPLICATIONS

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The response of materials to high-dose x-ray exposures needs to be understood for inertial fusion energy (IFE) and inertial confinement fusion applications, where the requirements for IFE are considerably more stringent. In the IFE context, x-ray damage and/or small levels of ablation are of importance for component survivability, generation of debris, and contamination. Ablation quantities of even 1 angstrom per shot would result in material removal of more than 1 cm per year of operation. If even one part in a million of this material made its way to the final optics, it would coat them with a thickness equivalent to several waves of the laser light. Also, small-scale melting and thermomechanical effects, such as fatigue, can result from x-ray heating. These effects potentially become important when multiple shots are considered, and thus, their study requires use of rep-rated experiments. As a part of the High-Average Power Laser Program, the XAPPER experiment has been initiated at Lawrence Livermore National Laboratory. XAPPER produces high doses of low-energy x-rays at repetition rates of up to 10 Hz. Study of x-ray damage is underway. An overview of facility capabilities, results to date, and future plans are provided.

I. INTRODUCTION

The XAPPER x-ray damage experiment has been established at Lawrence Livermore National Laboratory (LLNL). XAPPER's mission is to study the damage resulting from exposure to multiple x-ray pulses at *sub-threshold* fluences, where sub-threshold is defined as levels at which single-shot effects are not expected (e.g., melting or vaporization of the material). Study of laser-induced damage of aluminum mirrors has shown this to be of concern.[1] Materials of interest are first wall and final optics candidate materials for an inertial fusion energy (IFE) power plant. For dry-wall IFE, first wall candidates include tungsten armor on a ferritic steel substrate and a carbon-based material such as carbon-fiber composites. For the final optic, a grazing incidence aluminum mirror is the leading candidate, but thin, a transmissive fused silica Fresnel lens is another option.

For study of ablation in inertial confinement fusion (ICF) facilities, many materials are of potential interest. Examples include stainless steel, which can be used as a first wall, fused silica when used as a final optic, and aluminum alloys, which are often found in diagnostics or elsewhere within the target chamber. The key advantage of XAPPER, relative to other testing methods, is the ability to perform a large number of shots, thereby reducing detection limits and increasing statistical confidence.

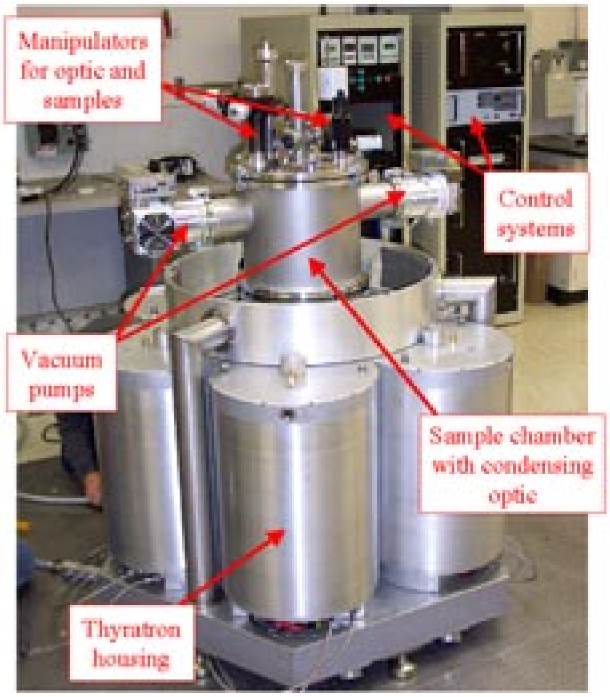
II. EXPERIMENTAL LAYOUT / CAPABILITIES

XAPPER is based upon a soft x-ray source designed and manufactured by PLEX LLC. The source is based upon a gas pinch: a pre-ionization current is put through the gas cell, followed by a main pulse of ~100 kA. XAPPER is currently operated with xenon discharges, but operation with argon, nitrogen, and other gases is possible. Repetition rates of up to 10 Hz are supported. A more detailed description of the source is given in Ref. 2. Figure 1 is a picture of the system installed at LLNL.

II.A. System Layout

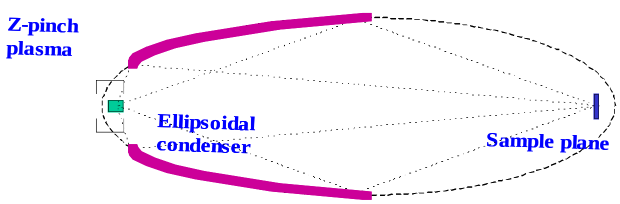
For the XAPPER experiment, the system geometry is ellipsoidal, with the plasma head sitting at one focus of the ellipsoid, and the sample to be irradiated sitting at the other focus. The system geometry is depicted in Figure 2. An ellipsoidal condensing optic is used to collect x-rays and bring them to focus at the sample. Debris is reduced through the use of a foil comb, which limits the plasma output to those angles incident upon the optic; there is no line-of-sight between the plasma head and the sample being irradiated.

Figure 1. The XAPPER experiment utilizes an EUV source designed and built by PLEX LLC.



The ellipsoidal condensing optic can be manipulated along the x-, y,-, and z-axes, where the pinch axis occurs along the z axis. The sample tray can hold up to five samples at a time; manipulation in θ rotates each successive sample into the focused x-ray beam. The sample tray also can be moved along the z axis.

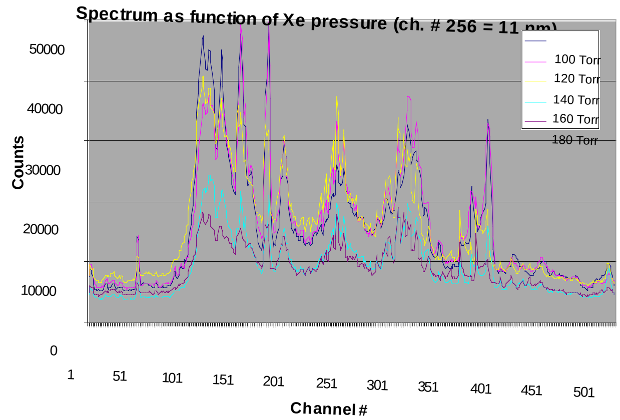
Figure 2. The plasma source and sample sit at the foci of an ellipsoid with a condensing optic between them.



II.B. X-Ray Output

The x-ray output can be tuned in terms of the fluence and, to an extent, the x-ray spectrum. The fluence can be altered by filtering of the unfocused beam or by an adjustment of the sample tray position (e.g., placing the sample a bit before or after the focus). Additional options include adjustment of operating pressure or discharge voltage. The latter two also can be used to adjust the x-ray spectrum. Figure 3 is a plot of the x-ray spectrum as a function of the xenon injection pressure, ranging from 13-24 kPa (100-180 Torr).

Figure 3. The x-ray spectrum from a xenon discharge varies as a function of the xenon pressure.



While the x-ray spectrum is considerably softer than that expected in an IFE power plant, the relevant figure of merit is not the x-ray energy, but the x-ray dose. Soft x-rays have rather short penetration depths, and thus, their energy is deposited within a relatively small mass. This results in very large x-ray doses.

The first two ellipsoidal condensing optics, provided by a PLEX LLC subcontractor, have failed to meet specifications. Focused x-ray fluences have been limited to ~0.2 J/cm^2. As a result, optics are being produced in-house by a team in LLNL’s Chemistry and Materials Science Directorate. By comparison with the x-ray microscope optics that being produced by this group, XAPPER’s condensing optic has relatively loose specifications. Mandrels are being fabricated and polished by an outside firm, and the coating process will be completed by mid-September. While the earlier optics suffered from a mid-frequency spatial roughness, it is expected that the replacement optics will be sufficient to provide a focused EUV fluence in excess of 1 J/cm^2. This fluence would be sufficient to melt tungsten.

III. MODELING

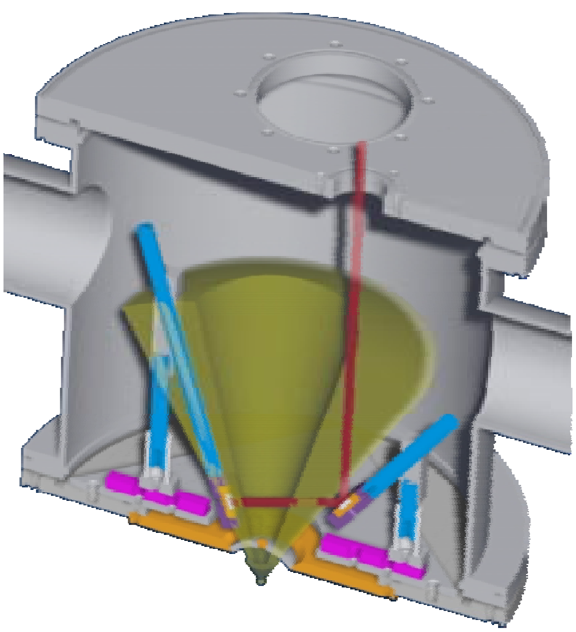
For experimental modeling, XAPPER uses the ABLATOR code.[3] ABLATOR is a 1-D finite difference code for the calculation of material response to x-ray exposure. ABLATOR’s major limitation is its use of cold opacities, but this is rarely an issue for the present work, where we are studying sub-threshold x-ray damage. The four major processes included in ABLATOR are energy deposition, transient thermal conduction, thermal expansion/hydrodynamic motion, and material removal through vaporization and various spall processes.

For the present work, ABLATOR has been updated and upgraded in several ways. First, the IFE x-ray output spectra, calculated by Perkins, have been implemented.[4] Second, ABLATOR has been updated to enable multi-material calculations. This was necessary in order to model tungsten armor on a ferritic steel first wall and for modeling of x-ray damage to aluminum-coated mirrors. Finally, a series of usability modifications were made and several materials were added to ABLATOR's databases.

IV. DIAGNOSTICS

XAPPER is equipped with several diagnostics for measurement of source output and overall system performance. These include time-integrating and time-resolved photodiodes (International Radiation Detectors, Inc.), a vacuum calorimeter (Scientech), and a 1-m grazing incidence x-ray spectrometer (built by McPherson). An in-situ optics damage measurement system, shown schematically in Figure 4, will be implemented in early September. A beam profiling system is being purchased, and a non-contact optical thermometer—designed by the University of California at San Diego—will be installed and tested in October.

Figure 4. Aluminum optics will be probed with low-energy laser pulses while undergoing exposure to soft x-rays at grazing incidence.



V. RESULTS

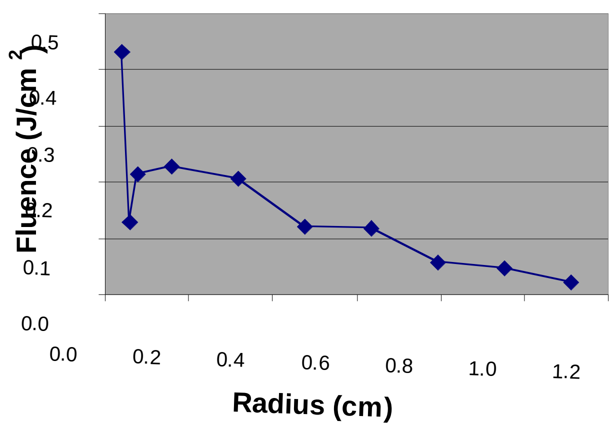
Thus far, the majority of XAPPER experiments have been focused on system characterization in terms of pulse energy, fluence, and spot size. Additionally, exposures of aluminum mirrors and tungsten (both foam and ordinary forms) have been completed.

V.A. Energy Measurements

Photodiode and calorimeter measurements of the focused x-ray beam have been completed. The time-integrated photodiode (AXUV100) includes an on-chip filter of 50/200/70 nm of titanium/molybdenum/carbon, which only passes photons from 5-15 nm. Pinhole measurements using the AXUV100 photodiode indicate a focused x-ray fluence of ~0.15 J/cm^2.

Calorimeter results do not discriminate according to photon energy, and thus, higher fluences are measured. The calorimeter has been used with a series of apertures in an attempt to construct a picture of the beam profile. Figure 5 is a plot of our data. The results suggest a central high-intensity spot that is surrounded by a lower-intensity "wing." Note that ~15× as much energy sits outside a 3-mm-diameter spot as that which sits within it. Use of a higher quality optic should significantly raise the central fluence.

Figure 5. The focused x-ray spot has been profiled using a calorimeter along with a series of apertures.



Future beam profiling measurements will be made with a large-aperture EUV filter (Luxel Corp.) and a fluorescer coupled to a scanning slit and a camera (Photon, Inc.).

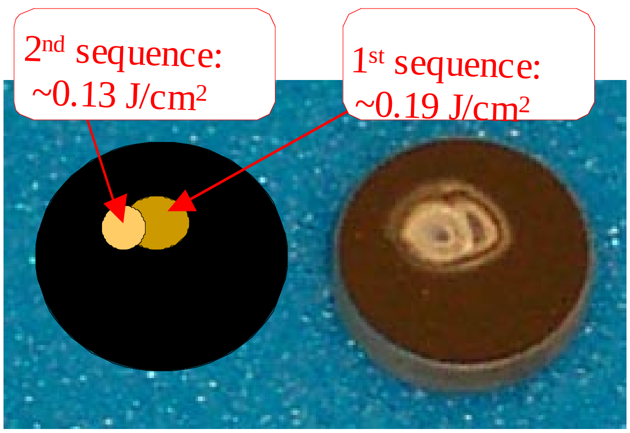
V.B. Exposure of Aluminum Mirrors

A series of Al/SiO_2 mirrors have been exposed on XAPPER. In order to prove that the observed damage is due to x-rays rather than ions (a concern due to the use of a pinch-based source), a simple experiment was conducted. Using an AL2 mirror from Newport, an exposure to 3000 pulses was completed at 8 Hz. Following this, the ellipsoidal condensing optic was moved slightly, and the exposure was completed for an additional 3000 pulses. Prior to the first exposure, photodiode measurements indicated an x-ray fluence of

0.19 J/cm^2. Following the second exposure, the photodiode indicated a fluence of 0.13 J/cm^2. A reduction in the fluence is to be expected, as the focusing optic was intentionally misaligned.

Figure 6 is a photo of the damaged mirror, along with a sketch of the experiment. Note that the damage spot moves between the first and second exposures. While this is to be expected if the damage is caused by x-rays, it would not occur if ions were responsible for the damage to the mirror.

Figure 6. Movement of the focusing optic resulted in movement of the damage on a test mirror. This proves that x-rays, rather than ions, have caused the damage.



V.C. Exposure of Tungsten

Samples of powder metallurgical tungsten, provided by Lance Snead at Oak Ridge National Laboratory, have been exposed on XAPPER. Although XAPPER's fluence is currently lower than that desired for such testing, our colleagues felt that such a test was still of interest. Specifically, two, 3-mm-diameter samples were exposed to 0.18 J/cm^2 for 10,000 and 79,500 pulses.

White-light interferometry (WLI) of these and a control sample revealed local high-spots on the sample exposed to the most pulses. Several groupings of spikes that are ~20 μm in diameter and 300-400 nm in height were found. Such formations were not found on either the control sample or the one exposed to 10,000 pulses.

While these results are far from conclusive—the spikes could be due to debris emitted from the plasma head—it is interesting to note that they are consistent with unpublished findings by T. Renk (Sandia National Laboratory, Albuquerque) that show tungsten surface roughening occurs at temperatures of 1500-2000 K.[5] Future work will include use of WLI both before and after exposure. Future samples will be mounted for easier and less destructive handling, and anomalous spikes will be tested chemically (this was not possible with the previous samples due to use of a tungsten plug, whose erosion would not be discernable from the tungsten sample).

VI. CONCLUSIONS AND FUTURE WORK

The XAPPER experiment has been installed at LLNL for the testing of IFE first wall and final optic materials. The facility provides high doses of soft x-rays at repetition rates of up to 10 Hz. To date, nearly two million pulses have been completed. XAPPER is configured with various energy, beam, and spectral measurement techniques.

By October 2003, XAPPER will be supplied with a greatly improved set of focusing optics, which will boost the x-ray fluence from <0.2 to more than 1 J/cm^2. These optics will enable full testing of tungsten and other candidate first wall materials. Completion of the in-situ optics damage measurement system (September 2003) will launch the campaign for testing of final optics under simulated, IFE-like conditions.

ACKNOWLEDGMENTS

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REFERENCES

1. M. R. ZAGHLOUL, M. S. TILLACK, and T. K. MAU, "Laser-Induced Damage of Metal Mirrors Under Long-Term Exposure at Shallow Angle of Incidence," 19th SOFE, Atlantic City, NJ, Jan. 21-25, 2002.
2. M. McGEOCH, "Radio-Frequency-Preionized Xenon Z-Pinch Source for Extreme Ultraviolet Lithography," *Appl. Optics* **37** (1998) 1651-1658.
3. A. T. ANDERSON, A. K. BURNHAM, M. T. TOBIN, and P. F. PETERSON, "Modeling and Experiments of X-Ray Ablation of National Ignition Facility First Wall Materials," *Fusion Technol.* **30** (1996) 757-763.
4. L. J. PERKINS, M. TABAK, R. BETTI, A. SCHMITT, and S. OBENSCHAIN, "High-Yield, Direct-Drive Targets for Inertial Fusion Energy," Presented at the Third International Conf. on Inertial Fusion Sciences and Applications, Monterey, CA, Sep. 7-12, 2003.
5. T. RENK, personal communication, Jul. 11, 2003.