STREAKED X-RAY MICROSCOPY OF
LASER-FUSION TARGETS

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Abstract

An ultrafast soft x-ray streak camera has been coupled to a Wolter axisymmetric x-ray microscope. This system was used to observe the dynamics of laser fusion targets both in self emission and backlit by laser produced x-ray sources. Spatial resolution was 7 μm and temporal resolution was 20 ps. Data is presented showing the ablative acceleration of foils to velocities near $10^7$ cm/sec and the collision of an accelerated foil with a second foil, observed using 3 keV streaked x-ray backlighting. Good agreement was found between hydrocode simulations, simple models of the ablative acceleration and the observed velocities of the carbon foils.
Introduction

An important area which has not yet been extensively experimentally explored in Inertial Confinement Fusion (ICF) is hydrodynamics. Theoretical work, on the other hand, has been extensive, making this area ripe for experimental study. Traditionally hydrodynamics has been studied through the use of high speed photography and radiography; however, traditional techniques are inadequate for ICF applications. Old technologies must be extended and new techniques must be developed to simultaneously achieve shorter time exposures and higher spatial resolutions. We have taken a step in that direction by combining the new technology of Wolter AxiSymmetric X-Ray MicroScope (ASXRMS) fabrication with the extended technology of the LLNL ultrafast Soft X-Ray Streak Camera (SXRSC). This combination provides the high temporal (20 ps) and spatial (7 μm) resolution required for many ICF target observations. Figure 1 on the previous page shows a schematic of the streaked x-ray microscope system as it was configured on the SHIVA laser target chamber and (with some improvement) as it will be configured on the NOVETTE target chamber. In both cases the streaked x-ray microscope is located on the equator of the target chamber with a line of sight in the plane perpendicular to the beams. There are three major components to the streaked x-ray microscope: the ASXRMS, the SXRSC, and the optical alignment system.
The Wolter Axisymmetric X-Ray Microscope

The Wolter ASXRMS is a grazing incidence hyperboloid ellipsoid x-ray mirror similar to the hyperboloid paraboloid x-ray mirrors used in satellite x-ray astronomy. However it requires higher surface tolerances because of the spatial resolution necessary to adequately observe the ICF target performance. Wolter ASXRMS's are of interest because they have a collecting solid angle several hundred times larger than the simpler and more common Kirkpatrick-Baez X-Ray Microscope (K-B XRMS). X-rays are reflected from the surface by total external reflection as described by Compton and Allison. For x-rays to be reflected by total external reflection they must strike the surface at a shallow angle. This is because at x-ray wavelengths the index of refraction of most materials differs from 1 by less than a part in 10,000. For a given x-ray energy, x-rays striking the surface at greater than a certain angle, the cut off angle, will no longer be reflected. Likewise, x-rays striking the surface at a given angle will not be reflected if they have greater than a certain energy, the cut off energy. The Wolter ASXRMS we have made has a nickel reflecting surface and is designed so the x-rays strike the surface at an angle of 1 degree. Figure 2 shows the ray paths through the ASXRMS. The x-rays from the laser fusion target reflect off the hyperboloid of revolution and then on to the ellipsoid of revolution. After reflection from the hyperboloid the rays appear to come from a virtual image at the second
focus of the hyperboloid which is by design coincident with one of the foci of the ellipsoid. It is a well known fact that rays coming from one focus of an ellipse will refocus at the other focus of the ellipse. The theoretical on axis resolution of such an x-ray optic is extremely high. It can be shown that the diffraction limited resolution of an annular optic is comparable to that of a full lens the same size. Thus the diffraction limited resolution of an x-ray mirror such as ours would be \( \lambda/120 \) A while geometrical aberrations would limit the theoretical resolution to 0.45 \( \mu m \) at 150 \( \mu m \) off axis in the object plane. In practice resolution is limited to about 1 \( \mu m \) due to imperfection of the x-ray optical surface. Surface slope errors of less than 0.01 arcsecond and profile deviations of only a few angstroms would be needed to yield diffraction limited performance. Slope errors between 0.6 and 0.8 arcseconds and profile errors of \( \pm 30 \) A have been achieved. Figure 3 shows a plot of the deviation of one of the mirror surfaces from the ideal profile. A perfect surface would appear as a straight line. The Wolter ASXRMS in the streaked x-ray microscope has a magnification of 22. When this is combined with the 150 \( \mu m \) resolution of the SXRSC the overall system resolution is limited to about 7 \( \mu m \). Thus for present uses 1 \( \mu m \) resolution is more than adequate for the ASXRMS. A more significant limitation of the ASXRMS is its small depth of field, about 7 \( \mu m \) for 1 \( \mu m \) resolution. This results from the large convergence angle of the rays at the object. An effective cure for this problem is to use a sector
(≈1/20) of the ASXRMS. This limits the convergence angle of the rays to a much smaller value and increases the depth of field to about 100 μm. The apertured Wolter ASXRMS still has about 20 times more collecting solid angle than a K-B XRMS.

Surface imperfections also have another important effect on the performance of the mirror. If surface roughness is greater than 10 to 15 Å, significant scattering of the x-rays will take place causing degradation of the mirror's reflectivity and throughput. The Wolter ASXRMS used in these experiments has the theoretical reflectivity for x-rays below 1.5 keV and drops linearly to 30% of theoretical at 3 keV. The effective collecting solid angle of the mirror is $1.5 \times 10^{-4}$ sr at 1.5 keV and $5 \times 10^{-5}$ sr at 3.0 keV. In the normal sectored operating mode these solid angles would, of course, be reduced by a factor of 20. This reflectivity suggests that the surface roughness of the mirror is about 15 Å.

**Ultrafast Soft X-Ray Streak Camera**

The soft x-ray streak camera used in the streaked x-ray microscope is a type which was developed at Lawrence Livermore National Laboratory and has been described previously. It was also described in greater detail elsewhere in these proceedings and in the literature. It uses the RCA C73435 streak tube which has had the optical photocathode
removed and replaced with a demountable thin foil soft x-ray photocathode. The thin foil is mounted on a carrier assembly which makes it easy to handle. In the experiments described later the photocathode was 300 Å of gold deposited on a 50 μg/cm² carbon foil. The cathode to anode voltage can range from 12 to 17 keV depending on the various grid and focus voltages. The camera on the streaked microscope was used at 15 keV and had a geometrical magnification of 1.35. The streak tube is followed by a 40 mm ITT microchannel plate (MCP) intensifier which is operated at an optical gain of about $10^4$. The streak is recorded on Royal X Pan film (ASA 2000) with a step wedge for calibration. With typical development the film has 4 orders of magnitude dynamic range. Static resolution of the streak camera is better than 11 lp/mm; however, when used dynamically with the MCP intensifier the resolution is degraded to about 3.3 lp/mm. The camera is a quantum detector and quantum statistical noise is a major limitation to image quality. Individual electrons emitted from the photocathode (quantum efficiency 0.01 to 0.2 in the 100 ev to 10 keV range) are recorded as spots on the film with a photographic density of about 1 and a FWHM diameter of 100 to 150 μm diameter. We believe that modifications to the intensifier will help improve the resolution and such options are being explored. The camera is driven by an electronically triggered avalanche transistor sweep circuit and is typically used at a sweep speed of 8.5 mm/ns, although it can be operated as fast as 25 mm/ns. The
time resolution of the camera is limited by electron velocity dispersion to about 20 ps. This is also the limit due to the spatial resolution of the intensifier at sweep speeds of 8.5 mm/ns. Dynamic range of the camera has been demonstrated to be between 1000 and 10,000. While the camera has operated very well there are some features we would like to improve; these include providing accurate alignment of the slit perpendicular to the sweep axis and fiducials on the film to allow accurate measurement of the streak record relative to the true streak axis. These features currently limit the accuracy of hydrodynamic measurements. We would also like to incorporate improvements in the MCP intensifier which would reduce the broad wings on its point spread function (also known as veiling glare).

Optical Alignment System

The optical alignment system (Figure 1) of the streaked x-ray microscope allows it to be pointed at a particular spot on a target to an accuracy of ± 5-10 μm. This is required so that the slit will pass precisely across the compression spike of a high convergence target which might typically be only 10 to 20 μm in diameter. The optical alignment system makes use of a visible light lens mounted accurately concentric with the Wolter ASXRMS mirror. The lens is made to have the same optical conjugates as the x-ray mirror and it is bench aligned so that its object and image foci are coincident with those of
the x-ray mirror. The lens can then be used to observe the target on virtually the same line of sight as the x-ray microscope. The visible light image of the target is observed using a movable beam splitter which can be repeatably inserted into the beam, and a camera and crosshairs which are rigidly attached to the streak camera. A visible image can simultaneously be projected on both the photocathode and the optical camera. Once the alignment camera and crosshairs are adjusted to be coincident with the slit of the streak camera and locked down alignment can be carried out using the optical camera alone. This provides a much higher quality alignment image than would be obtained by observing the image projected on the streak camera photocathode. The alignment camera image is several orders of magnitude brighter, yielding short exposure times and can be seen well with the naked eye. The alignment lens does present one small problem, in that if it were left uncovered during a shot a significant amount of light would be focused on the photocathode of the streak camera, probably destroying it. This problem is solved by blocking the lens during a shot with a tantalum disk 2.5 cm in diameter and 1 cm thick. The disk performs the additional function of protecting the streak camera from high energy x-rays (< 100 keV) from the target which would pass straight down the line of sight, bypassing the mirror. The shadow cast by the disk is about 60 cm in diameter at the location of the streak camera.
In addition to the alignment lens and camera the alignment system also incorporates a mercury arclamp illuminator which is focused from the far side of the target chamber by a 1 m focal length lens to back-illuminate the target during alignment. A second lens which is annular collimates some of the light from the arc lamp into an annular beam which is projected across the target chamber and is reflected off an annular concave mirror surrounding the alignment lens. The light from the concave mirror front illuminates the target so that it can be observed in reflected light. Both front and back illumination are essential for the degree of visibility which is required for accurate alignment of the camera to the target.

**Laser Driven Foil Acceleration Experiments**

The streaked ASXRMS described above has been used at the Shiva laser facility to observe the laser driven ablative acceleration of carbon foil targets to velocities greater than $10^7$ cm/s. The experiment was performed at LLNL in collaboration with NRL and examined a laser produced plasma parameter regime not previously studied. This regime was characterized by moderate laser intensity ($10^{14}$ W/cm$^2$), large spot size (1 mm), long scale length plasma ($\sim$0.3 mm), long pulse length (3 to 3.5 ns), large laser pulse energy (3 to 3.5 kJ), and good beam uniformity. Figure 4 schematically shows the target geometry used in the experiment. The target
foil was carbon with a density of $2.0 \text{ g/cm}^3$, $10 \mu\text{m}$ thick and $3 \text{ mm}$ wide. Measured areal densities were used in all calculations. The impact foil, into which the target foil collided, was typically about $8 \mu\text{m}$ thick, $3 \text{ mm}$ wide, and was mounted nominally $200 \mu\text{m}$ behind the target foil. In some cases the impact foil was omitted and only the ablative driven target foil was observed. The target foil was irradiated in the near field of Shiva's lower beam cluster. Overlapping the 10 lower beams on the $1 \text{ mm}$ spot is expected to result in $3 \times$ statistical improvement in irradiation uniformity. Time integrated x-ray microscope images indicate $50\%$ spatial intensity modulation on 10 beam shots with pulse length reduced to $100 \text{ ps}$ to limit lateral energy transport. The carbon foils were backlit with the $2.9 \text{ keV}$ line radiation of ionized palladium, emitted from a laser irradiated backlighter foil. The backlighter foil was mounted on the same target structure as the carbon target and impact foils, about $3$ to $4 \text{ mm}$ from the carbon foils. A $75 \mu\text{m}$ thick beryllium foil was used to shield the accelerated carbon foil from preheat caused by soft x-rays ($<1 \text{ keV}$) and superthermal electrons ($<50 \text{ keV}$) emanating from the backlighter, while still passing the $2.9 \text{ keV}$ backlighter radiation. Eight to ten beams from Shiva's top beam cluster were used to irradiate the backlighter target at $2 \times 10^{14} \text{ W/cm}^2$. The beams were overlapped on the backlighter target to provide statistical smoothing as described above. The backlighter pulse was the same length as the drive pulse, but delayed by $1 \text{ ns}$. This allowed us to view more of the
target's trajectory, since it covers very little distance during the first 1 ns.

When the laser beam hits the carbon target foil, the foil dimples out away from the laser, driven by the pressure (~6 Mbar) of the ablated carbon. The laser spot is substantially smaller than the width of the foil so the part of the foil not irradiated by the laser is not accelerated and remains at its initial position. Figure 5 shows a streaked image of the shadow of a single foil target which was accelerated to 1.2 x 10^7 cm/s. The light region in the photo is the backlighter covering the field of view of the camera. The dark triangular area which gets wider from left to right is the shadow of the ablatively accelerated carbon foil. The lower edge of the triangle is caused by the part of the foil which did not move.

Preliminary analysis of the backlighting data from the single foil experiment (Fig. 5) involves fitting of second and third order polynomials to the upper edge of the shadow of the moving carbon foil. At present data is extracted from the streak photo by fitting a smooth continuous curve to the photo by eye. The curve is then digitized and the polynomial fit performed on the digital data with an interactive program on a DEC VAX computer. The procedure is carried out this way since the sophisticated image processing software to extract the edge and correct for backlighter intensity variations in the presence of substantial statistical noise (maximum signal
levels were about 100 photons detected per pixel) is not yet available. However, curves obtained in this way appear to be quite reproducible and accurate to about one pixel (≈6-7 μm). The position and velocity versus time histories are quite reasonable and agree well with the hydrocode calculations. A good average acceleration value is also obtained. It is true, however, that small errors in position for the points digitized from the original data lead to increasingly large errors for higher derivatives of the position data. These errors limit extraction of the acceleration data by this method to its average value with limited temporal history.

One approach to overcoming this problem is to theoretically establish the functional form which the trajectory can take and then adjust the free (but empirically constrained) parameters to fit the measured data. We have tried this approach with reasonable success. This procedure is carried out by formulating the equations of motion (the rocket equations) using the theoretically derived scaling relations for the ablation pressure, blow off velocity and mass ablation rate as a function of laser intensity. These scaling relations have also been supported empirically and by LASNEX calculations. The scaling relations are:
Mass ablation rate;
\[ \dot{m}(t) = \dot{m}_0 (I_a(t))^\alpha \], where \( \alpha \approx 0.6 \) \hspace{1cm} \text{Equation 1}

Blow off velocity;
\[ v(t) = v_0 (I_a(t))^\beta \], where \( \beta \approx 0.2 \) \hspace{1cm} \text{Equation 2}

Ablation pressure;
\[ P(t) = \dot{m}_0 v_0 (I_a(t))^{\alpha \beta} \], \hspace{1cm} \text{Equation 3}

where \( v_0 \) and \( \dot{m}_0 \) are the blowoff velocity (cm/s) and mass ablation rates (g/cm\(^2\)s) at 10\(^{14}\) W/cm\(^2\) effective absorbed intensity (\( v_0 \) and \( \dot{m}_0 \) are not initial values).

The blow-off velocity scaling exponent, \( \beta \), is most frequently found to be 0.22 to 0.25 in the theoretical literature\(^{14-23}\) and has been found to be consistent with 0.2 empirically\(^{24}\).

The mass ablation scaling parameter, \( \alpha \), is most frequently found to be 0.56 to 0.50 theoretically\(^{4-23}\), and is empirically consistent with 0.6\(^{24}\). In the following analysis we have assumed \( \alpha = 0.6 \) and \( \beta = 0.2 \). \( I_a \) is the effective absorbed intensity as a function of time in units of 10\(^{14}\) W/cm\(^2\). \( I_a \) is defined as follows:

\[ I_a(t) = \frac{f_d I_i(t)}{E} \] \hspace{1cm} \text{Equation 4}

\[ \int_{-\infty}^{\infty} I_i(t) \, dt = \frac{F_i}{A} \times 10^{-14} \] \hspace{1cm} \text{Equation 5}
where $E_i$ = incident laser intensity (J)
$A$ = nominal laser spot area (cm$^2$)
$f_a$ = fraction of laser light absorbed (from scattered light diodes)
$e$ = ratio of the effective spot size (from streaked optical pyrometry) to the nominal beam spot size (from target alignment photos)
$I_i$ = the incident laser intensity
$I_a$ = the effective absorbed laser intensity.

The time dependence of $I_i$ is derived from optical streak camera records of the laser pulse, while the magnitude is derived from calorimetry.

The effective spot size is measured from the size of the shock breakout at the back of the impact foil (on double foil shots), with a streaked optical pyrometer. Light is emitted at the time the shock emerges from the back of the impact foil. The fastest part of the target foil will reach the impact foil sooner and therefore cause an earlier shock breakout, slower portions will be delayed. The effective spot area is defined to be the area of the target which has been accelerated to at least 60% of the peak velocity. The spot area measured in this way was 2.2 times larger ($e = 2.2$) than the nominal laser spot area, i.e. the spot diameter was 1.5 times larger. The larger effective spot size and lower effective laser intensity
is presumably due to some or all of several energy transport mechanisms, including light refraction in the blow off plasma, lateral thermal conduction, Brillouin side scatter, and superthermal electron transport.

The rocket equation arises from Newton's law, which together with the above scaling laws yields the scaling law for the foil acceleration:

$$a(t) = \frac{P(t)}{M(t)} = \frac{\dot{m}_0 v_0}{M_0} \left[ I_a(t) \right]^{q_B} \int_{-\infty}^{t} \left[ I_a(t') \right]^a \, dt'$$

Equation 6

where $a = \text{the foil acceleration}$,

$P = \text{the ablation pressure (Eq. 3)}$,

$M = \text{the areal mass}$.

All are functions of time. $M(t)$, the denominator in the right hand side of Equation 6, is just the initial areal mass, $M_0$, reduced by the integrated mass ablation. In our experiment the ablated mass is small compared to the initial mass so the numerator of Equation 6 dominates the time dependence. Thus a measurement of the acceleration is nearly a direct measurement of the pressure, with only a small correction necessary. The velocity and position as a function of time are obtained by integrating Equation 6 with initial conditions of zero velocity and acceleration (Eq. 7 and 8).
\( v(t) = \int_{-\infty}^{t} a(t') \, dt' \) \hspace{2cm} \text{Equation 7}

\( x(t) = \int_{-\infty}^{t} v(t') \, dt' \) \hspace{2cm} \text{Equation 8}

For some simple approximations to \( I_f(t) \) these equations can be integrated in closed form. However, in this experiment \( I_f(t) \) was measured and the equations could be numerically integrated. Measured values were also available for \( f_a, \varepsilon \) and \( M_o \), and \( a \) and \( \beta \) were assumed to have the values given above. We allowed \( m_0 \) and \( v_0 \) to vary and adjusted them for the best fit to the data.

Figure 6 shows, as a function of time, the laser intensity (6a), the foil acceleration (6b), the foil velocity (6c), and the foil position (6d). Points from the LASNEX hydrocode calculations are also shown (L). In Figure 6 the center of the laser pulse occurs at 3.8 ns. The timing, relative to the analytic model and to LASNEX code calculations is absolute \( \pm 100 \) ps. The best fit of the numerically integrated position from Equations 6, 7 and 8 matched the polynomial fit to the data to \( \pm 2 \, \mu \text{m} \) over the entire region measured by the streaked x-ray microscope (2.5 to 6 ns in Fig. 6). The best fit occurred with \( m_0 = 3.17 \times 10^5 \, \text{g/cm}^2 \, \text{s} \) and \( v_0 = 5.25 \times 10^7 \, \text{cm/s} \). The peak pressure was 6.3 Mbar \( \pm 15\% \). The measurement tends to be rather sensitive to the product of \( m_0 \) and \( v_0 \) which is directly related to the
acceleration and the pressure, but not to either one separately. This is because as long as the product remains constant, either one can vary as the reciprocal of the other without significantly changing the result. This is of course only true if the ablated mass is small. If the ablated mass were a large fraction of the total, the experiment would be much more sensitive to the parameters in the denominator of Equation 6, \( \dot{m}_0 \) and \( \alpha \). The values for \( \dot{m}_0 \) and \( v_0 \) agree quite well with the values in Reference 24 when corrections are made to account for experimental differences in spot size definition. This measurement provides both an accurate value for the ablation pressure and the efficiency with which laser light is being coupled into kinetic energy. A velocity of \( 1.2 \times 10^7 \) cm/s gives the central 1 mm diameter portion of the foil a kinetic energy of 90 J. This represents approximately 7% of the laser light incident on that portion of the target foil. With a preheat level of about 15 eV (measured by streaked optical pyrometry), the foil has about 10 times as much directed kinetic energy as internal thermal energy.

X-ray backlighting experiments were also performed on double foil targets as shown in Figure 7. Preliminary analysis of the data indicates that the irradiated foil reaches a velocity of \( 7 \times 10^6 \) cm/s before impact with the second foil at somewhat more than half way through the laser pulse. At the time of the collision both foils have a nearly equal areal
density of $1.5 \times 10^{-3}$ g/cm$^2$. The second foil thus attains a velocity of about $7 \times 10^6$ cm/s from the collision, as may be seen in Figure 7. Also visible in Figure 7 is the decompression of the impact foil due to preheat, at a velocity of about $10^6$ cm/s.

Conclusion

We anticipate that these experiments will lead to the development of a capability to make accurate ablation pressure measurements on laser driven targets as well as measure the efficiency with which laser energy is converted to kinetic energy. The experimental results described above are consistent with both LASNEX calculations and with the simple scaling model described, increasing our confidence in our ability to predict the behavior of laser fusion targets. Other interesting measurements will be made in the area of hydrodynamic instabilities in the future. Improvements being made on the streaked x-ray microscope will enhance the quality of the quantitative measurements obtained through this type of high speed photography.
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Figure captions:

Figure 1. Streaked Wolter axisymmetric x-ray microscope system.

Figure 2. X-ray paths through a Wolter ASXRMS

Figure 3. Deviation of Wolter ASXRMS surface from the ideal profile. A perfect mirror would appear as a straight line.

Figure 4. Target geometry used in carbon foil acceleration experiments observed with x-ray backlighting.

Figure 5. Streaked x-ray microscope record of single foil slab acceleration experiment.

Figure 6. a) Laser pulse incident on carbon foil.
   b) Acceleration history of carbon foil.
   c) Velocity history of carbon foil.
   d) Position history of carbon foil.

Figure 7. Streaked x-ray microscope record of a colliding foil experiment.
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Figure 7. Streaked x-ray microscope record of a colliding foil experiment.
Virtual image

Hyperboloid
Ellipsoid

Object
(laser fusion target)

Aperture stop

F1H, F1E

F2H

F2E

Image

FIG. 2
FIG. 3
FIG. 4
$E_i = 2.95 \text{ kJ}$

$A = 7.85 \times 10^{-3} \text{ cm}^2$

(1 mm dia. spot)
\[ P_{\text{max}} = 6.3 \text{ Mbar} \]

\[ f_s = 0.6 \]
\[ c = 2.2 \]
\[ m_0 = 3.17 \times 10^5 \text{ gm/cm}^2 \text{s} \]
\[ v_0 = 5.25 \times 10^7 \text{ cm/s} \]
$f_s = 0.6$
$\hat{c} = 2.2$
$\dot{m}_0 = 3.17 \times 10^5 \text{ gm/cm}^2 \text{ s}$
$v_0 = 5.25 \times 10^7 \text{ cm/s}$

FIG. 6c
\( f_a = 0.6 \)
\( \phi = 2.2 \)
\( m_o = 3.17 \times 10^6 \text{ gm/cm}^2 \text{ s} \)
\( v_o = 5.25 \times 10^7 \text{ cm/s} \)

FIG. 6d
Streaked x-ray backlit image

FIG. 7