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Target Physics Results at 248 nm Wavelength from the Aurora Laser System High-Intensity Campaign

By

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Abstract

Au and Si targets have been irradiated using the Aurora KrF laser system, and diagnosed with x-ray and optical diagnostics. The x-ray diagnostics were sensitive to the 0.1–10 keV range. Initial, manually aligned results indicate significant plasma heating and intense x-ray production, with incident peak intensities on target of $1\text{--}2 \times 10^{14}$ W/cm² in a focal spot of order 500 μ m diameter. Total energy delivered to the target in 36 of the available 48 target beams was approximately 1200 J in pulses with FWHM in the 3–5 ns range. M-band radiation was observed from Au foil targets. Initial bandwidth measurements on the laser indicate ≈ 20 cm⁻¹ without bandwidth enhancement efforts.

Introduction

Results over the last ten years indicate that the laser-target coupling efficiency of laser driven inertial confinement fusion (ICF) improves dramatically with reduced laser wavelength. Other characteristics including large bandwidth (200–400 cm⁻¹) and flexible pulse shape capability (with contrast ratios between the foot and the main pulse > 10) also appear to be very beneficial to high gain target performance. Excimer gas and frequency multiplied glass laser systems are being considered as candidates for the required short wavelength driver for ICF applications. Los Alamos National Laboratory has

recently completed construction of Aurora, the first KrF excimer laser system capable of focussing energies in excess of 1 kJ at 248 nm wavelength on an ICF target. Target physics experiments used to characterize the delivered beam properties and conduct initial laser-target interaction studies with the Aurora system will be discussed in this report.

Initial target physics experiments have concentrated on moderate atomic number planar targets in order to achieve large x-ray fluxes. The emission characteristics of Au and Si discs have been studied using a variety of x-ray detection devices. The results of this study were used to characterize, indirectly, the laser focal spot properties. These results and other laser system measurements have been combined to evaluate initial Aurora performance characteristics. Parameters achieved in this early work comprise energies up to 1.5 kJ in 36 of the 48 available beams, delivered to target in a 5 ns FWHM pulse. Focussed peak intensities in the range $1\text{--}2 \times 10^{14}$ W/cm² are estimated from a combination of x-ray imaging and delivered power measurements. The appearance of weak M-band radiation in the x-ray spectrum of Au disc targets is consistent with this intensity range. Delivery of the remaining 12 beams to target (currently intercepted for diagnostic purposes), combined with repair of currently damaged optical components in the main laser chain and operation of the high-power amplifiers closer to their design points, will significantly increase these parameters in the next 6 months. Detailed laser physics studies have also been done on the system, with results to be reported elsewhere.

1 Laser system description

Aurora is an angularly multiplexed, 96 beam, KrF laser system, operating at 248 nm wavelength and multikilojoule energy levels. (Of the total 96 beams, 48 beams are currently brought to target.) The system consists of 5 distinct sections: the front end, temporal encoder, high-power amplifiers, temporal decoder, and target facility. Detailed descriptions of these sections have been covered in a series of articles in Fusion Technology.¹ The basic system will be outlined here to orient the reader during discussions of interstage and target facility diagnostics. A conceptual schematic of the overall system is shown in Fig. 1.

The front end (FE) is a discharge laser based system, using a stimulated Brillouin scattering (SBS) cell as a phase-conjugate back mirror in the second gain stage to control prepulse, risetime, and pulse duration. The output of the second gain stage is further amplified and split into two distinct beams,

each containing 100–500 mJ in a pulse 1–5 ns FWHM in duration. These two beams are delayed 30 ns with respect to each other and then delivered to the beam expander and spatial slicer in the main laser system.

The two expanded beams are split into 6 pieces, by spatial slicing of the beam cross section in the first part of the temporal encoder. The 12 resulting beams are angularly and temporally recombined into a pulse train 60 ns in duration, for further amplification. The 60 ns pulse train is sent through the first E-beam pumped amplifier (Small Aperture Module [SAM], a 10x10x100 cm³ cross section, two pass module) where its energy is increased to the 1–5 J range. The 60 ns pulse train is subsequently split into 8 parts and delayed in the second half of the encoder, resulting in 96 individual beams covering a time window of 480 ns. The beams are angularly and temporally recombined into a 96 pulse train of nominal 480 ns duration for further amplification. The final pulse train is injected into the centered optical system at the Preamplifier (PA) input feed array (IPA), consisting of 96 independent, computer aligned mirrors. The 96 beams are spatially overlapped for the first time at the input pupil to the centered optical system.

The resulting pulse train is amplified by three subsequent, large aperture, KrF modules: the PA (a 20x20x280 cm³, E-beam pumped, single pass amplifier), the IA (Intermediate Amplifier, a 40x40x280 cm³, E-beam pumped, single pass amplifier), and the LAM (Large Aperture Module, a 100x100x200 cm³, E-beam pumped, double pass amplifier). The 96 beams are temporally separated, but spatially overlapped through each of these amplifiers, with spatial separation occurring between stages. The spatially separated beams are fed into the LAM by 96 independent, automatically controlled mirrors at the LAM feed array (FA), located approximately 70 m down stream from the IA output window and 85 m from the LAM back mirror. The final high energy output beams from the LAM are spatially separated at the recollimator array (RCA), located 106 m from the LAM back mirror. After recollimation into 14x14 cm² square beams, 48 of the 96 beams are temporally decoded using time-of-flight in the decoder, after which the beams are sent simultaneously to target.

Final overlap of the beams on target is performed by 48 independent final aiming mirrors ultimately controlled by a dedicated alignment system computer. For initial operation, the 48 final aiming mirrors were manually controlled by target alignment personnel, with the beam overlap process being completed typically within 90 minutes of the first beam being aligned to the lensplate. (Beam stability over this alignment period is adequate to maintain the focal spot within approximately 500 μ m, suitable for preliminary target experiments.) Final focussing on target is accomplished by 48 F/26 lenses,

arranged in an F/2 bundle, allowing single side illumination of planar targets. Focus is controlled by a single axis controller capable of moving the entire lensplate, and its 48 focussing lenses, simultaneously, throughout a range of +12.5/-2.5 mm with respect to the target plane. The entire lens cone and target chamber (1.57 m diameter sphere) are under vacuum, separated by a gate valve to allow the target chamber to be brought to ambient pressure independently. The target is placed at focus by an insertion mechanism with independent vacuum system capabilities, allowing target insertion without target chamber venting to atmosphere. Initial focussing and beam overlapping were conducted using a visible image of the 248 nm overlap on a fluor at target center observed by a telescope and imaged on a TV monitor.

2 Diagnostic complement

Laser and target diagnostics provide information on the overall performance of the system and the response of the target to the delivered laser radiation. The energy levels of pulse trains and individual beams are monitored throughout the main laser chain utilizing a combination of commercial surface and bulk absorbing calorimeters designed for operation at 248 nm. In addition to these energy meters, laser power waveforms captured by several photodiode-based power-monitoring systems may be integrated to evaluate the percentage of total measured energy present in the main laser pulse, as opposed to the energy content in any toe or tail present. The power history is observed by photodiodes at many locations throughout the chain. Very high time resolution instruments (2.5-6 GHz analog bandwidth) monitor front end laser output and time resolved soft x-ray emission. Details of the diagnostic complement, as well as a description of the data acquisition system used for the measurements reported here, are given in the following laser and target diagnostic sections.

2.1 Laser interstage diagnostics

The front end energy output is measured for each beam by surface absorbing calorimeters that observe a 4% reflection from each of the two windows between the front end and the encoder area. The full aperture power history of the two output pulses is monitored by a 6 GHz analog bandwidth, digitizing oscilloscope in combination with two 60 ps risetime vacuum photodiodes. This yields a combined system response with ≤ 100 ps 10-90% risetime. Fast details of the front end pulse are studied with this system but will not be discussed here.

The two pulse shapes are observed individually in the encoder, before spatial slicing, by twin, subaperture ($\approx 50\%$ area) sampling, 270 ps 10-90% risetime vacuum photodiodes. These signals are simultaneously observed by the 6 GHz oscilloscope and digitized by a 1.35 GS/s, 400 MHz analog bandwidth, storage module for later analysis. The power envelope at approximately 300 MHz bandwidth is used as the basic pulse shape reported in this work, for both the front end output pulse and elsewhere throughout the system. The 96 pulse train constructed from these individual beamlets is monitored by a similar 300 MHz bandwidth system at the PA input pupil for overall beam train structure. Pulse train energy is monitored by surface absorbing calorimetry at the same location.

After separation at the LAM feed array and the recollimator array, individual beamlets from the unused 48 beams are analyzed. Energy is measured by full beamlet aperture bulk absorbing calorimeters at the feed array and by partial and full aperture calorimeters at the recollimator. Extrapolated equivalent 96 beam energy estimates are based on the mean and standard deviation of a small number (4-6) of sampled beams at each location. This 96 beam extrapolation is subject to large uncertainty due to observed differences in energy extraction between the first and second 48 beams. This energy extraction difference is associated with the relative timing between the pulse train and the LAM pump cycle. This timing effect will be discussed in a later section. Individual power histories are observed throughout the system using 300 MHz detection systems. One of the unused recollimator beams is re-collimated and sent to the far end of the beam tunnel. Energy measurements at the array and at the far end are used for high-power tunnel absorption measurements, to estimate the relative energy loss due to ozone absorption and other contaminants.

Amplified spontaneous emission (ASE) energy losses at 248 nm from a KrF laser depend on whether or not energy is being extracted from the gain region by loading with an external laser pulse train. ASE emitted perpendicular to the laser pulse direction is monitored in the four E-beam amplifiers by 248 nm filtered, 270 ps diodes combined with 32 MS/s, 100 MHz analog bandwidth digitizers. Suppression of the unloaded ASE level during the pulse train is used to insure that the input pulse is correctly timed with respect to the E-beam pump cycle.

2.2 Laser beam delivery diagnostics

Laser performance is monitored in the used 48 beams subsequent to the recollimator array. Energy delivery during these early experiments was esti-

mated by fully capturing 12 of the 48 incident beams at the lensplate with full aperture bulk absorbing calorimeters. The 36 beam energy on target was estimated from the mean and standard deviation of the 12 sacrificial beams, which were spread uniformly throughout the first 48 beamlets. Energy balance was estimated from the spread in the intercepted beam energies, and LAM timing was adjusted as required to minimize both systematic trends and root-mean-square variation in this spread. In addition to the intrusive calorimeters, other calorimeters were placed behind the decoder mirrors to observe leakthrough for selected beamlets. These leakthrough measurements will ultimately be cross calibrated to the intrusive calorimeters to allow all 48 beams to go to target while maintaining an energy diagnostic traceable to the intrusive set.

The power history was estimated from full aperture samples of the leakthrough behind several decoder mirrors. These full aperture samples utilized integrating sphere detectors with spherical, anodized, metal reflectors, acting as quasi-diffuse mirrors, which collected light from the entire beam foot print and directed it to photodiodes. The detectors were either 60 ps or 270 ps risetime vacuum photodiodes or 1 ns Si diodes, depending on the plug-in used in the integrating system. Small aperture power samples were present behind several decoder mirrors as well. Because beam to beam variation appears to be less for full aperture samples than for partial aperture samples, full beam samples are used as the power history monitor in this report. Absolute power history was estimated from the combined energy and power diagnostics, corrected for actual beam count on target. Comparison of the 300 MHz bandwidth energy pulse shape throughout the system shows little obvious temporal distortion.

Laser bandwidth was diagnosed with a 1 m spectrometer, centered at 248 nm, observing leakage behind the decoder mirror for beam 27, near the center of the used 48 beams temporally.² Data from this instrument were taken on photographic film for later densitometer scanning. Instrumental resolution was 0.03 nm, a factor of three less than the observed bandwidth of approximately 0.1 nm ($10\text{--}20\text{ cm}^{-1}$). Instrumental resolution was checked using a Hg line near the laser wavelength (253.6 nm). Film exposure response curves produced with a 20 ns KrF laser were used for film correction.

Laser spot size estimates and final alignment were provided using a fluor sensitive to 248 nm and a telescope to observe the resultant visible emission. Visible 35 mm pictures of the fluor provided archival images of both individual beams and the overlap. A charge-coupled device (CCD) camera also observed the fluor. This image will be recorded for comparison with the x-ray images to be discussed later.

2.3 Target physics diagnostics

Except for the fluor and optical telescope used for both alignment and 248 nm spot size estimates, the target diagnostics used in these early target physics experiments were all soft x-ray diagnostics in the 0.1–10 keV spectral region.

Time integrated x-ray emission was observed by a set of hard film based x-ray pinhole cameras with magnifications of 2, 4, and 8. These imaging systems were placed at 45 and 30 degrees to the target plane to observe the laser deposition area, as well as in the equatorial plane to observe transverse plume expansion. The cameras consist of either 3 or 6 pinholes per camera, with diameters of 12.5 or 25 μm per pinhole. The pinhole cameras are mounted on independently pumped insertion mechanisms to allow retraction and reloading without venting the target chamber to ambient pressure. Densitometer scans of the film have resolutions of the image in the target plane in the 13–31 μm range. (The resolution in the target plane is affected by the magnification [2–8x], pinhole size [12.5 or 25 μm], and densitometer scan aperture [25–50 μm].) These cameras are capable of resolving images in various energy ranges, depending on the filter placed in front of an individual pinhole. For the experiments reported here, filters ranged from a low of approximately 200 $\mu\text{g}/\text{cm}^2$ of aluminum on plastic, with a low energy cutoff below 100 eV, to a high of 4 μm of Be with a cutoff energy well above the 2 keV range. The more heavily filtered camera images typically were primarily sensitive to the Au M-band emission (2–2.5 keV).

Time integrated x-ray spectra were measured with a transmission grating spectrograph and a curved crystal spectrograph. The first instrument was sensitive in the 0.2–2 keV range, while the second was sensitive in the 1.4–2.7 keV range. Both instruments were film based, requiring post-shot densitometer scanning.

Time resolved x-ray emission³ from the plasma was detected by MultiFlex⁴, a seven channel, aluminum photocathode based photodiode system. MultiFlex is sensitive, dependent on filtration, to x-rays in the 0.1–10 keV range. This system was simultaneously monitored by seven 2.5 GHz analog bandwidth oscilloscopes and by the 300 MHz digital system used for several diagnostics throughout the chain. This soft x-ray system will provide one of the elements of an upcoming x-ray conversion efficiency campaign, in conjunction with the spectrographs, laser energy and power monitors, and a 248 nm scattered light system currently undergoing testing in the target chamber.

2.4 Data acquisition

Waveform data acquisition was done using a combination of fast oscilloscopes and digital storage modules. The oscilloscopes used have a range of analog bandwidth (ABW) capabilities: 6 GHz (Tektronics 7250 digitizing oscilloscope), 2.5 GHz (Los Alamos Model 1776), 1 GHz (Tek 7104), and 500 MHz (Tek 7903). CAMAC based data storage was obtained from a variety of modules: LeCroy Research (LRS) 6880B (1.35 GS/s, 500 MHz/400 MHz [filtered] analog bandwidth [ABW]), LRS 8828/18B (200/100 MS/s, 100 MHz ABW), LRS 8837 (32MS/s, 100 MHz ABW), LRS 8212 (32 channel, ≤ 40 kS/s, 50 kHz ABW). Non-CAMAC based digital voltmeters (Keithley Model 199/1992, 8 channel, 5 S/s, 1 kHz ABW, 10 μ volt sensitivity) were also used. Note that signals are transported to waveform collection locations by a minimum of approximately 15 m of high speed coax (signal speed 88% of the speed of light) yielding an upper bandwidth limit of approximately 2-3 GHz at all locations. The highest speed CAMAC modules are used to sample the laser pulse energy delivery envelope at approximately 300 MHz system ABW as discussed earlier. The slow speed digitizers were used exclusively for calorimeter recording, where the thermal response time is typically several seconds.

Laser power was monitored by either 60 ps 10-90% risetime vacuum photodiodes (Hamamatsu model R1328U-02) or a larger active area 270 ps 10-90% vacuum photodiode (Hamamatsu R1193U-02). Surface absorbing calorimeters with approximately 100 μ sec 10-90% risetime (GENTEC model EDV-500) were used to measure low energy levels in the front end and at the PA input pupil. Laser beamlet energy was monitored using large diameter bulk absorbing calorimeters with risetimes of more than one second (Scientech model 38-0803 with 8 inch active area and Scientech 38-0403 and 38-4UV5 with 4 inch active area).

The digital data was acquired and analyzed using IBM AT compatible 80386 computers with 80387 math coprocessors at various locations throughout the facility. Acquisition software was developed inhouse over the last several years for a series of laser-target interaction experiments. The software is written in Microsoft QuickBasic Ver. 4.0, using National Instrument's GPIB boards and the libraries designed for use with them. User controlled software capabilities include the usual arm/trigger/read cycle, baseline viewing, module register setup, and several waveform display routines. File export in several forms is provided to allow further analysis external to the acquisition system.

3 Experimental results

The experimental series reported here consisted of numerous target shots at energy levels below 100 J (IA level shots) and a more limited number at energy levels between 500-1500 J on target (LAM level). In all cases ≤ 36 beams were taken to target, the other 12 being sacrificed for diagnostic purposes. The IA level shots were used predominantly for system integration and checkout and have been adequately described in other internal documentation.⁵ The data to be discussed here were taken at LAM level. Shot to shot variations were significant due to the immature nature of the Aurora laser system.

3.1 Laser parameters

Because of the exploratory nature of these early shots, a number of laser pulse shapes, amplifier timings, amplifier voltages, and fill pressures were used during the study. The latter two control settings affect predominantly the total energy content and will not be discussed further. (Typically, higher voltage and fill pressure result in higher output energy but the parameter space is not fully documented to date.)

The pulse shape observed during the experiments varied from a 7.5 ns FWHM main pulse frequently followed by a tail, which contained significant amounts of the total energy (early in the study), to a much cleaner pulse with controlled FWHM in the range 2.5-5 ns late in the study, as operating characteristics and requirements were optimized. Figure 2 shows an overlay of the pulse shape observed behind one of the decoder mirrors for several different types of pulse. This plot, and all subsequent laser power plots, are taken from the 300 MHz digital data store. The plot shows the tail mentioned earlier and is a full aperture sample taken from one of the quasi-integrating sphere detectors used to observe leakthrough behind many of the decoder mirrors. By the end of the experiment, this tail was reduced to negligible levels by front end modifications. The final pulse shape used in the experiment is shown in Fig. 3 for the 3.5 ns FWHM pulse duration. The FWHM of the pulse, as seen by this low time resolution system, did not vary appreciably throughout the chain from the encoder area to the decoder area. (Higher frequency behavior, such as the 50-100 ps FWHM leading edge spike⁶ seen in the front end room, was not investigated during this campaign.)

Pulse train timing with respect to the LAM E-beam current has repercussions in the energy balance in the first (or second) 48 beams. Figure 4 shows this effect. For a nominally temporally centered beam train (solid bars),

there is a marked trend to higher energy later in the train. This results in a large RMS spread in beamlet energy estimates based in the 12 beam mean and standard deviation. For a delayed train (hatched bars), where the first 48 beams are closer to the center of the LAM gain pulse, this trend is significantly suppressed. Target physics experiments reported here were taken predominantly with the delayed timing to improve beam balance and allow more accurate estimates of total energy on target due to the reduced RMS variation in that case. The best beam balance achieved in the series was $\pm 19\%$ RMS for the 3-5 ns FWHM pulses used near the end of the experiment. Note that delaying the train with respect to the LAM may have prelate repercussions due to unloaded ASE in the LAM that could be deleterious to some classes of target physics experiments. Such problems were not of concern in these early experiments. The fluctuation from beam to beam in the histograms in Fig. 4 appear to be fairly constant from shot to shot and probably reflect variations in individual surfaces throughout the chain. No conclusive data dealing with atmospheric transmission losses due to absorption by ozone or other contaminants are yet available.

Near field burn patterns taken after the LAM in unused beams show variations across the footprint. In particular, for pulses late in the 96 pulse train, using delayed timing of the optical pulse train with respect to the LAM, clear indications of low E-beam penetration due to the water line voltage running down at the end of the cycle are seen. This effect is shown dramatically in Fig. 5. In both burn patterns in Fig. 5, the north side of the LAM is to the right in the image, with the top being up. The upper image in Fig. 5 (a negative of the original burn pattern) is for beam 66 on shot 2649, a normal shot with nondelayed timing, showing reasonable near field energy uniformity. The lower pattern in the figure is for beam 66 on shot 2678, in which the LAM, particularly on the north side, prefired severely, in addition to being delayed for better target beam balance. In this shot the water lines, particularly on the north side, were far below their peak voltage at the time beam 66 traversed the LAM, resulting in very poor apparent E-beam penetration and resultant laser gain in the center of the LAM cavity. (Note that the switch failures resulted in lowering the delivered target energy from about 1.3 kJ in 2649 down to 0.28 kJ in 2678.) Optical damage in the chain and variations in the turbulence induced convection cell patterns are also reflected in the near field burn patterns but are not an inherent part of the laser operation and will not be discussed here.

The laser spectral bandwidth is of considerable interest to the ICF community because of potential suppression of long scale-length instabilities afforded by a combination of short wavelength, wide bandwidth, and spatial

incoherence.⁷ Bandwidth as large as 200 cm^{-1} is believed to be possible with KrF laser systems. Spectral content was monitored behind one of the decoder mirrors. Figure 6 shows a comparison of spectra between a LAM level shot and several front end level reference shots. The main line appears to be composed of several lines whose relative amplitudes determine the overall line. The line width of the composite spectra varies between $10\text{--}20\text{ cm}^{-1}$ from shot to shot, as measured with an instrumental width of 4 cm^{-1} . This appears to be the result of front end variation, as shown in Fig. 6, rather than some effect due to the power amplifiers. The observed bandwidth was present without any attempt to broaden out the front end output. (The front end bandwidth used in this campaign has, in fact, been narrowed by insertion of a prism in the oscillator cavity to limit the growth of the focal spot in the target plane due to bandwidth effects in the refractive optics in the system. In addition to this, the SBS phase conjugate mirror in the second stage also limits the present bandwidth.)

3.2 Target plane parameters

The target plane during these experiments was normal to the axis of the incident bundle of laser beams. Typically the x-ray camera viewed the emission from this target from a location 45° from the normal. The raw x-ray image of a typical 36 beam shot on a Au disc is shown in the contour plot in Fig. 7. This image is taken with a 1.9 mil Be filter in front of a $25\text{ }\mu\text{m}$ pinhole at 8x, with a $26\text{ }\mu\text{m}$ resolution. The x-ray cutoff for this filter (with the x-ray spectrum observed in this series) occurs at approximately 1.7 keV, so only the central hot plasma regions are observed by it. (Taken by itself, this image, with FWHM of $< 450\text{ }\mu\text{m}$, containing perhaps 50% of the 940 J delivered over a FWHM of 3.7 ns, would imply an average intensity of order $8 \times 10^{13}\text{ W/cm}^2$ on target. Better analytical techniques and results will be discussed later.) Five other filter packs were also present on this camera ranging from 1.3 mil Be (sensitive above 1.2 keV) to 4 mil Be (sensitive above 3 keV). On other shots, smaller pinholes were used to reduce the light admitted to the camera so that lower energy filtration could be used. In all cases, the lower the cutoff energy, the larger the image. This effect is not pronounced until the filter cutoff is down to the several hundred electron volt range where heating by lateral energy transport is particularly visible. (FWHM increases by $< 8\%$ from 1.9 mil down to 1.3 mil Be, for the same shot on the same camera.) The slight flattening seen in the image is caused by the viewing geometry. Figure 8 is a surface plot of the raw data in Fig. 7.

To interpret the image on the x-ray film, one must understand the results

of the viewing geometry. This geometry is shown in Fig. 9, in which a simple hemispherical emitting region of diameter $650\text{ }\mu\text{m}$ is viewed at 45° to its normal. Shown in the figure is the line of sight to the film (dashed lines), the hemisphere (shaded area), and the slant range through the hemisphere seen at 45° to normal (solid, skewed curve). The viewing angle results in a skewing of the slant range with respect to the cosine distribution seen normal to the region, which in turn results in a compression of the film image on one side. In addition to this compression, the 45° film plane also compresses the image uniformly by a factor of 0.707 with respect to the target plane dimensions. In the event that the emitting plasma is of uniform temperature and density (unlikely), and that the plasma is optically thin to the monochromatic x-rays observed in this model, this slant range would be linearly related to the image observed on the film. If an axial expansion occurs between the hemispherical cap and the target plate, that effect can be modeled similarly.

The above considerations imply the need to perform several operations on the image as seen on the film in order to interpret it. Stretching the horizontal axis of the image by a factor of $\sqrt{2}$ to account for the film plane angle results in the contour plot seen in Fig. 10. The dimensions in this plot are those in the target plane, so that the diameter of the emission can be read directly. In addition, the skew of the image can be compared to that caused by the slant range effects discussed above. This comparison is done for a horizontal lineout of the image in Fig. 11, comparing the data (solid curve) and the slant range through a uniform $650\text{ }\mu\text{m}$ diameter hemisphere viewed at 45° , normalized to the same maximum value. The agreement between the slant range and the observed lineout suggests that the plasma is at least optically thin to the x-rays so the entire emitting sphere is represented rather than some annular region. It also implies that any temperature and density contours for the plasma conditions resulting in this image are nearly spherically symmetric. The slant range skew comes out in the integral over energy and plasma regions, just as in the case of the monochromatic, uniform emitter discussed above. Figure 12 is a vertical lineout of the same image, in which case neither of these corrections need be applied. The model comparisons suggest that this image was caused by a hemispherical plasma of diameter $650\text{ }\mu\text{m}$, which includes any expansion due to the long time duration of the plasma cloud. As can be seen from the lineouts, the peak to valley variation in emission in the image, on a scale larger than the $26\text{ }\mu\text{m}$ resolution (4 pixels) of the system, is less than 15%. The exact connection between the x-ray emission uniformity and the uniformity of the incident laser focal spot depends strongly on the exposure time, energy band, and thermal smoothing that may occur in the plasma. Details of these processes require simulation with

a numerical code, such as LASNEX, before comparison between experiment and theory can occur.

About 2 mil Be is used as a benchmark for focal spot size in these experiments (as well as at other laboratories) because it is predominantly sensitive to M-band radiation from Au targets. Such an image does not see the expanding, cold plasma cloud that occurs after the main laser pulse turns off. This cloud, at temperatures well below 100 eV, has been observed with Kimfoil filters ($192 \mu\text{g}/\text{cm}^2$ aluminum on plastic) and typically has a diameter 2-3 times that of the M-band emission region. The cold cloud continues to radiate for some period of time after the drive pulse is gone, expanding at the same time. Therefore, size estimates of the interaction region made from Kimfoil data would overestimate the size of the region by a large amount, dependent on the expansion velocity.

To properly interpret the x-ray images, one needs knowledge of the spectral shape. The time integral x-ray spectra, taken during this experiment and shown in Fig. 13 and Fig. 14, are for 36 beam shots on Au and Si discs respectively. In each case the benchmark features of the spectra are identified. The Au spectra can be compared to similar spectra taken at the Omega laser⁸ at 3ω ($\approx 350 \text{ nm}$) to help benchmark the present plasma. The important features noted in that experiment were that the position of the N-band peak varies with intensity and that to turn the M-band on requires some minimum intensity. In the case of Aurora, intensities of approximately $1 \times 10^{14} \text{ W}/\text{cm}^2$ are required for both the observed shift and the presence of M-band radiation (as calculated from the Omega data scaled by $I\lambda^2$ to apply to 248 nm). Both observations, when compared to the present data, support intensities in this series in the $100 \text{ TW}/\text{cm}^2$ range, consistent with the x-ray image interpretation.

Typical time resolved x-ray data seen with MultiFlex in the 0.1-10 keV range are shown in Fig. 15. These waveforms were captured with 2.5 GHz bandwidth scopes capable of detecting much faster features than other data discussed; such features are not dominant in these data. Because the cutoff energies in these waveforms are well below 1 keV, the data are inherently somewhat different in content from the x-ray images discussed above. In particular, the lowest energy channel (Kimfoil) is sensitive to emission from the cold expanding cloud after the shot. The apparent FWHM of the various channels clearly decreases with increasing cutoff energy, as one would expect. (The higher energy x-rays require higher intensities to create their higher temperature source plasmas, with the higher intensities only present during the peak of the pulse.) The lowest energy channel shows evidence on some shots of a toe before the main pulse due to plasma created by whatever

prelase may be present. The radiation after the pulse is somewhat obscured by the presence of the timing fiducial. Both of these effects make estimates of the duration and emission intensity of any cold expanding cloud difficult. It is not yet possible to estimate the long time effects the prelase (which is currently under investigation) and postemission might have on low energy x-ray images. For this reason, in LAM level shots, the low energy images are disregarded in spot size analysis as discussed above.

4 Discussion

Further data reduction beyond the simple average intensity estimates made above based on the spectra and on the FWHM of the x-ray image require some type of model for the laser profile and its relation to the x-ray image. Neglecting film corrections on the x-ray image, the simplest model equates the x-ray emission and laser intensity spatial profiles. (In the region of interest, using the SB5 x-ray film utilized here, film response correction is in fact quite minimal, and would result in a slight narrowing of the image and consequent increase in calculated peak intensity.) Further image analysis can be performed on the x-ray image with this model to extract the intensity profile for the incident laser. It is important to note that the following analysis *assumes* that any laser radiation that actually made it to target focussed in the observed area. In the event some part of the incident measured energy actually spread out into a very low intensity pedestal of large diameter, where the intensity was insufficient to create a plasma and produce x-radiation, the following analysis would utilize an over-estimate of the energy on target. This would directly lead to an over-estimate of the peak intensity based on this calculation. The existence of M-band radiation appears to support the conclusion that the available energy did reach the focus, but some uncertainty remains. Assuming that the spatial and time dependence are separable, the functional form for the incident laser intensity may be written as

$$\phi(x, y, t) = \phi_0 v(t) h(x, y),$$

where ϕ_0 is the peak intensity, $v(t)$ is the time dependence measured from the photodiode full area samples, and $h(x, y)$ is the x-ray (and laser) spatial profile, measured under the above assumptions. Both of the functions involved are normalized to unity so that the peak intensity ϕ_0 can be derived from the integral of this function. (Note that the spatial integral is multiplied by a factor of 1.4 to correct the effective area for the 45° view angle in the horizontal plane. No attempt to correct for the slant range effects discussed earlier

has been made.) Noting that the integral over time and space of $\phi(x, y, t)$ is the total on-target energy, one can calculate the peak intensity

$$\phi_o = E_{total} / (\int v(t) dt * \int h(x, y) dx dy).$$

This is the formula used to produce the peak intensities listed in Table 1. A peak flux may also be calculated assuming that both the power and profile have Gaussian waveforms. The peak flux derived from the mathematical model above lies between the average flux estimated in the data section ($E_{total} / (\tau_{FWHM} A_{FWHM})$) and the peak from the Gaussian model. This indicates that the waveforms are not in fact truly Gaussian but somewhat skewed to be broader than a simple Gaussian, particularly in the power. This result is not unexpected since the usual behavior of the power pulse comprises a high peak followed by a somewhat lower plateau region as shown earlier in Fig. 2 and Fig. 3.

The laser intensities achieved in this campaign, along with the shot number, date, on-target energy in 36 beams (except shot 2680 which was 45 beams to target), FWHM of the drive pulse, FE output energies (beamlines 1/2), and peak power are shown in Table 1. The intensity uncertainty comes from a combination of uncertainties in the energy, peak power, and effective area (integral under the x-ray emission image). The main contribution comes from the beam to beam RMS variation in the energy, this contribution being typically in the 25-35% range during these early experiments. The second largest contributor is the effective area used, which could be as much as 20% low if a 1.2 keV energy cutoff image should really have been used rather than the higher energy image utilized. Opposing these errors are the effect of film correction and the time integral nature of the x-ray image, which allow the image to exceed the actual profile dimensions due to expansion. In addition, the temperature of the plasma is actually a very complex function of the laser-plasma interaction regime. Even in the simplest Inverse Bremsstrahlung Absorption case, without any instabilities, temperature really scales with incident intensity as ϕ^α , where α is a number somewhat less than one,⁹ implying some nonlinearity between the x-ray emission profile and the laser deposition profile. In order to improve our knowledge of the laser profile, some optical technique for measuring the high energy beam at 248 nm wavelength, in the overlap region, would need to be developed. LASNEX modeling may reduce the uncertainties associated with the connection between the x-ray image and the laser deposition profile.

High-Intensity Target Shot Series (8/15-9/7/89)

Date	Shot	FE (mJ)	E (kJ)	τ_L (ns)	P_0 (10^{11} W)	Φ_0 (10^{14} W/cm ²)
8/15	2645	211/296	1.29	7.0	1.5	>1.0
8/16	2648	236/263	1.31	6.0	1.6	2.2 ± 0.9
8/16	2649	155/238	1.13	7.0	1.5	>1.9
8/17	2652	19/20	0.96	4.5	2.1	>1.1
8/22	2661	18/18	0.85	5.0	1.6	>0.7
8/22	2662	16/16	0.72	3.5	1.8	1.5 ± 0.4
8/23	2664	15/17	0.91	3.5	2.2	1.2 ± 0.4
8/23	2665	15/18	0.58	4.0	1.4	
8/30	2670		0.25	3.5	0.66	1.1 ± 0.4
8/31	2673	8/9	0.94	3.5	1.9	1.1 ± 0.4
8/31	2674	7/9	0.84	3.0	1.9	1.3 ± 0.5
8/31	2675	9/11	0.90	3.5	1.9	1.1 ± 0.3
9/7	2678	7/7	0.37	4.5	0.78	0.8 ± 0.3
9/7	2680	7/7	0.74	4.0	1.8	1.1 ± 0.5

Conclusions

The experimental data taken during this early series on Aurora were predominantly designed to answer questions about laser suitability for ICF target experiments. The results presented indicate that even in its infancy, the KrF laser is capable of focussing large amounts of energy on target in a focal region small enough to produce intensities of interest to the ICF community. With improvements to the optical components and improved energy extraction from the LAM, at higher operating voltage, Aurora should be easily capable of peak intensities on target of order 1×10^{15} W/cm². This regime puts Aurora in the mainstream of ICF research facilities and implies a very productive experimental future for the system.

Acknowledgments

The work reported here involved the efforts of a large number of people on the Aurora laser operations team, the Aurora target physics team, and the laboratory ICF theoretical community. Without a concerted effort by all

concerned within P, CLS, and X divisions the present work could not have been accomplished.

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Figure 1. Conceptual schematic of the Aurora Laser Facility.

Figure 2. Three laser pulse shapes used during the High-Intensity campaign.

Figure 3. The ultimate pulse shape used during the latter stages of the campaign. Note that the remaining tail structure at levels of ± 1 division on this trace is instrumental in the digital data store. It is not really part of the pulse but rather a background noise component in the waveform.

Figure 4. A comparison between beam balance for a centered shot (solid bars) and a delayed pulse train shot (hatched bars). The delayed train (with respect to LAM) is desirable for target physics at this point because it results in smaller RMS variation in the energy spread in the first 48 target beams.

Shot 2649

Shot 2678

Figure 5. Comparative burn patterns for a nominal shot (2649) with normal water line operation in the LAM and a severely prefired shot (2678) with the diode voltage much lower than normal at the time this beam (66) propagated through the LAM gain media.

Figure 6. Laser spectra for several front end level and one LAM level shots. The spectrum for the LAM level shot was taken behind decoder mirror 27. The front end level spectra were taken with this mirror removed to eliminate the 98% reflection loss due to it and increase the system sensitivity.

Figure 7. Contour plot of a typical 36 beam x-ray image, with equal contour intervals, shown without any geometrical corrections applied.

Figure 8. Surface plot for the x-ray image of Fig. 7.

Uniform Hemispherical Emission

Figure 9. Model of the x-ray camera view of the target world, for a hemispherical, uniform, optically thin, emitter. The solid curve is the apparent integrated emission as a function of position in the target plane as seen along a 45° line of sight to the normal of the hemisphere. This model is for a hemisphere of diameter $650 \mu\text{m}$.

Figure 10. The contour plot of Fig. 7 with a horizontal stretch applied to remove the film plane tilt induced dimensional compression discussed in the text. Except for slant range effects, this image is what would be seen in the target plane.

Figure 11. Horizontal lineout of the xray image, corrected for the film plane tilt (solid curve) and the prediction for a simple, optically thin, uniform x-ray emitter viewed at 45° to the hemisphere normal (dashed curve).

Figure 12. Vertical lineout of the x-ray image (no corrections needed).

Figure 13. Observed x-ray spectrum from a Au disc target.

Figure 14. Observed x-ray spectrum from a Si target.

Figure 15. An overlay of observed MultiFlex soft x-ray time resolved data. The individual traces are not absolutely normalized but rather normalized to one to show the decrease in temporal FWHM with increasing cutoff energy.

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