APR 1 1988

CONF-880110--26

UCRL- 98386
PREPRINT

UCRL--98386

DE88 008038

SIMULTANEOUSLY TIME- AND SPACE-RESOLVED
SPECTROSCOPIC CHARACTERIZATION OF
LASER-PRODUCED PLASMAS

G. Charatis*, B.K.F. Young***, Gar. E. Busch*,
C.J. Cerjan**, W.H. Goldstein**, A.L. Osterheld**,
T.W. Phillips**, M.D. Rosen**, R.E. Stewart**,
and R.S. Walling***

*KMS Fusion, Inc., Ann Arbor, Michigan 48104

**University of California, Lawrence Livermore National Laboratory
Livermore, California 94550

+University of California-Davis, Dept. of Applied Science
Livermore, California 94550

This paper was prepared for submittal to: Proceedings of
"Optoelectronics and Laser Applications in Science and
Engineering", January 10-15, 1988, Los Angeles, CA
March 3, 1988

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Simultaneously Time- and Space-Resolved Spectroscopic Characterization of Laser-Produced Plasmas

G. Charatis*, B.K.F. Young**§, Gar. E. Busch*, C.J. Cerjan**, W.H. Goldstein**
A.L. Osterfield**, T.W. Phillips**, M.D. Rosen**, R.E. Stewart**, and R.S. Walling**§

*KMS Fusion, Inc., Ann Arbor, Michigan 48104

**University of California, Lawrence Livermore National Laboratory,
Livermore, California 94550

§University of California-Davis, Dept. of Applied Science, Livermore, California 94550

ABSTRACT

The CHROMA laser facility at KMS Fusion has been used to irradiate a variety of microdot targets. These include aluminum dots and mixed bromine dots doped with K-shell (magnesium) emitters. Simultaneously time- and space-resolved K-shell and L-shell spectra have been measured and compared to dynamic model predictions. The electron density profiles are measured using holographic interferometry. Temperatures, densities, and ionization distributions are determined using K-shell and L-shell spectral techniques. Time and spatial gradients are resolved simultaneously using three diagnostics: a framing crystal x-ray spectrometer, an x-ray streaked crystal spectrometer with a spatial imaging slit, and a 4-frame holographic interferometer. Significant differences have been found between the interferometric and the model-dependent spectral measurements of plasma density. Predictions by new non-stationary L-shell models currently being developed are also presented.

Experimental Overview

The determination of electron densities and temperatures of hot, dense plasmas using spectral line ratios can differ by large factors depending upon the assumptions used in the atomic physics model employed in interpreting the line ratios.¹ Moreover, transient and non-uniform plasma distributions may contribute to ambiguous interpretations of available data. In this paper, we present experimental measurements of x-rays emitted from laser-produced plasmas whose spatial and temporal gradients are either small or measurable. Using microdot target irradiation techniques² in conjunction with new time- and space-resolved diagnostics, we can determine temperatures and densities by standard line intensity ratio techniques and compare them to independent temperature and density measurements. This comparison allows us to make clear tests of theoretical atomic models upon which the line ratio methods are based.

In applying the microdot target techniques, small disks containing the elements of interest, were placed on plastic substrates. By illuminating the target normally with a laser spot larger than the microdot, the

surrounding carbon plasma from the target substrate, collisionally confined the test ions from the microdot into a well defined, slowly expanding (radially) plasma column. Using this microdot target design, the plasma conditions are expected to be uniform across any cross section of the plasma column. The remaining axial gradient along the laser axis, is resolved using an imaging slit. The target opacity was somewhat controlled by the density and diameter of the microdot test element. Temporal variations of the plume were detected using time-resolving diagnostic instruments. The electron densities determined by spectral line ratio methods were independently checked using holographic interferometry for the density.

Time- and Space-Resolved Diagnostics

These rapidly time and space varying laser-produced plasmas require sophisticated diagnostic methods to simultaneously resolved both spatial and temporal gradients. Spatial and temporal gradients were simultaneously resolved using 3 diagnostics: a 4-frame holographic interferometer provided non-spectroscopic determinations of the electron density³; line intensity profiles were measured with an x-ray streaked crystal

Figure 1. Schematic diagram of the experimental set-up illustrating the position of the principal diagnostics with respect to the irradiated microdot target.

Figure 2. Simultaneously time- and space-resolved K-shell and L-shell emission spectra from a $100 \mu\text{m}$ diameter MgBr dot irradiated by $8.5 \times 10^{13} \text{ W/cm}^2$ of 526.0 nm laser light in a 1.0 ns stacked pulse. The time frames are 450-700, 850-1100, and 1230-1480 ps, recorded by the FCXS.

Figure 3. Typical time-resolved spectrum obtained with the streaked spectrometer (XSCS), of a $100 \mu\text{m}$ diameter aluminum microdot. The spectrometer viewed the Al plasma plume 0 to $150 \mu\text{m}$ from the target surface.

spectrograph (XSCS) with a spatially imaging slit, and a 3-frame crystal x-ray spectrometer (FCXS)^{4,5}. These instruments were aligned to view the target edge-on, perpendicular to the laser axis and the plasma plume. (See Fig. 1) Additional plasma and laser diagnostics included two space-resolved, time-integrating flat crystal mini-spectrometers; one employing a high dispersion/high resolution crystal (ADP), while the other used a lower dispersion crystal (KAP) and served as a survey instrument. Two x-ray pinhole cameras measured the focal spot size and the uniformity of the plasma. An optical streak camera recorded the CHROMA pulse shape for each shot. The total absorbed laser energy was determined for each shot by using calibrated CHROMA laser optics and by recording the reflected laser light off the targets using an array of photodiodes located inside the target chamber. The optical parameters were useful for hydrodynamic simulations of the laser produced plasmas.

A set of x-ray spectra emitted by a typical 100 μm diameter MgBr target and recorded using the 3-frame FCXS instrument is presented in Fig. 2. A sample spectrum produced by a 100 μm Al microdot target and recorded with the XSCS time-resolving diagnostic is shown in Fig. 3. In both cases, the H-like and He-like resonance lines as well as the intercombination and dielectronic satellite lines are clearly discernible.

The Laser-Target Experiments

For all target shots, simultaneous measurements were made using all of the principal diagnostics. A variety of targets were irradiated including aluminum microdots

Figure 4. Time-integrated, space-resolved temperature measurements derived from an optically thick CRE model Al He α /H α line ratio are presented by a range of temperatures. This is due to uncertainties in the plasma density and opacity caused by the loss of information due to time integration.

and dots containing a mixture of bromine and magnesium. Typically, the microdots were 100 μm diameter mounted on thick polystyrene substrates. They were irradiated with a single CHROMA beam of 10 to 100 J of 526 nm light in a 1 ns long pulse (actually ten 100 ps pulses stacked in 100 ps intervals). Using an F/2.5 lens, the laser beam was focused on the target to a diameter of 250 μm resulting in irradiances of 10^{13} to 10^{14} W/cm². Unless specified otherwise, the data presented in this paper correspond to laser irradiances of 1×10^{14} W/cm² for the Al microdots and 2×10^{13} W/cm² for the MgBr target shots. The relative intensities of the measured spectra were corrected for film response, crystal reflectivities, filter transmissions, and photocathode efficiencies.

Electron Temperature Measurements

We have estimated the electron temperature by analyzing space-resolved, but time-integrated Al spectral data from the same target shots. The time integrated temperature profile determined from the line intensity ratio between the He-like $1s^2(^1S) - 1s2p(^1P)$ and the H-like $1s - 2p$ resonance lines, He α /H α , interpreted using a steady-state (CRE) atomic modeling code RATION/RATSHOW/ SPECTRA⁷, is presented in Fig. 4. The time-integrated profile represents a range of temperatures due to uncertainties in the time-varying electron density and due to line opacity effects. The uncertainty due to time averaging of the data is clearly large. Furthermore, it is very clear from the spectral data that the ionization distribution is far from equilibrium. Therefore it is very inappropriate to analyze the spectral data from this highly transient plasma using a (CRE) atomic code which is based on a equilibrium ionization distribution. A detailed analysis of time-resolved line intensity ratio diagnostics for the electron temperature is in preparation.⁸

Electron Density Measurements

The 4-frame holographic interferometer employed in the experiments used a 20 ps, 263.0 nm wavelength beam to probe the plasma. The probe pulse was synchronized to within 5 ps of the main CHROMA heating beam and was operated simultaneously with the time and space resolving spectrometers. The recorded holograms were reconstructed using a CW Argon laser providing two dimensional, axisymmetric interferograms. These were Abel inverted to yield spatially resolved density profiles at 4 pre-selected times during and after the CHROMA laser pulse⁹. A set of 4 on-axis density profiles for a typical 100 μm Al microdot shot is shown in Fig. 5.

The electron densities were also determined spectroscopically using the He-like $1s^2(^1S) - 1s2p(^1P)$ resonance

Figure 5. A typical set of four on-axis Al microdot electron density profiles obtained via holographic interferometry.

line (He_{α}) and the $1s^2(^1S)-1s2p(^3P)$ intercombination (IC) line ratio⁹, again using the RATION CRE modeling code. In Fig. 6, we compare the density profiles obtained by four different ways: (1) via holographic interferometry in which only the data spanning the same time and space as the spectral data is presented, (2) via LASNEX¹⁰ (2D hydrodynamic code) computer simulation, and by analyzing the $\text{He}_{\alpha}/\text{IC}$ line ratio using the (3) optically thin and (4) optically thick options of the RATION modeling code.

The density profile obtained from the LASNEX code simulation agrees exceptionally well with the interferometrically determined profile at 1457 ps and reasonably well with the profile at 1657 ps. The $\text{He}_{\alpha}/\text{IC}$

Figure 6. Comparison of electron density profiles obtained via holographic interferometry, LASNEX hydrodynamic simulation, and by applying optically thick and thin analysis of the CRE RATION atomic model to the $\text{He}_{\alpha}/\text{IC}$ line ratio.

ratio measurement for the optically thin case disagrees dramatically from the interferometry data. This is not unexpected since the He_{α} resonant line is optically thick especially near the target surface (at the higher electron densities) and also at these late time when the electron temperature is quite low. Also, at this late time after the heating laser is off, the plasma is clearly recombining and the CRE model should not be expected to be applicable. Surprisingly, we find good agreement between the spectral and interferometric density profiles when we apply the optically thick option in the RATION code assuming an effective plasma size of 50 μm . This finding is being further investigated.

L-Shell Spectroscopy

We have also conducted a series of experiments using composite targets which emit K-shell lines (to diagnose the plasma conditions) simultaneously with the L-shell emission spectra. This allows us to test potential plasma diagnostics based on L-shell emission spectra. Various pairs of low-Z / high-Z target mixtures were used including magnesium and bromine. The laser-produced plasmas were studied using the same array of diagnostics. Comparisons are made between electron densities derived from density sensitive K-shell and L-shell line ratio measurements as predicted by various atomic modeling codes and from holographic interferometry measurements.

A variety of L-shell diagnostic models and techniques for the element pairs tested are being examined and will be reported in later publications. For the present paper, we report on the comparison of experimentally measured density-sensitive L-shell transitions of Br (as

Figure 7. Comparison of electron density profiles obtained via holographic interferometry and using two neon-like Br resonance line ratios analyzed using the 37 level neon-like Br model.

represented by an atomic model) with interferometric measurements. The density sensitive nature of these neon-like Br lines is due to the existence of higher lying metastable levels. The metastable levels are also responsible for the population inversion that leads to lasing in neon-like ions¹¹. At low densities, these states decay by radiative cascades and contribute largely to the intensities of the two lowest energy (3s-2p) Br transitions. But as the electron density is increased, transitions due to electron collisions dominate the decay of these excited levels leading to a smaller fraction of electrons ending up contributing to the intensity of the (3s-2p) transitions. A simplified atomic model of the neon-like Br ion, which includes the lowest 37 states but ignores other charge states, predicts this behavior. The atomic model predictions can be checked experimentally via line ratio measurements. Previous time-integrated measurements were in good agreement with the model.¹² However, as illustrated in Fig. 7, the quantitative comparison of the model-predicted electron density profiles, using the (3s-2p)/(3d-2p) and the (3s-2p)/(3p-2s) line ratios, and the interferometry density profiles reveal the shortcomings of the atomic model.

Figure 8. Comparison of electron density profiles obtained via holographic interferometry and using the neon-like Br resonance line ratios analyzed using a (neon-like) Br model which also includes ionization and recombination contributions from neighboring charge states.

It has been noted¹³ that the simple model discussed above not only leaves out other high lying neon-like excited levels, but also ignores contributions due to recombination (mainly dielectronic recombination) and ionization from ions in adjacent charge states. These processes can lead to significantly different line intensities for the neon-like resonance lines being modeled. A calculation incorporating these atomic processes has been used to fit the neon-like resonance lines in our data. This more detailed atomic model is referred to in Reference 13. (A more complete

description of this model will be presented in the near future.) The densities predicted using this more sophisticated atomic model, are compared to the interferometry densities in Fig. 8. The results for the earliest time frame are in best agreement with the interferometric data. However, the trend in time does not match the experiment and further work is needed on the model.

Figure 9. Electron densities computed by a LASNEX simulation of a laser-irradiated bromine dot are compared to interferometry measurements.

The LASNEX simulation was also used as input for a detailed atomic model XRASER^{11,14} to generate a calculated bromine x-ray emission spectrum. This synthesized spectrum is generated using a post-processing, dynamic atomic model which is in a preliminary stage of development. A comparison of the calculated and measured spectra is shown in Fig. 10 and represents the emission recorded from a plasma region

Figure 10. A synthetic Br spectrum, produced by a post-processed LASNEX driven XRASER calculation, is compared to experimental data. The measured spectrum records the x-rays emitted from 30 to 90 μm from the target surface over a time interval of 840 to 1090 ps.

30 to 90 μm from the target surface over a time interval of 840 to 1090 ps. The spectral emission contributions due to the Mg ions are not included in the calculated spectrum. The simulated spectrum correctly predicts the dominance of neon-like and sodium-like Br ions, but does not account for the small fluorine-like component evident in the experimental spectrum. In addition, the relative intensities of the neon-like resonance lines are not reproduced. Such discrepancies may be due to errors in the ionization distribution predicted by LASNEX or by other shortcomings in the atomic model but this comparison provides a nice preview of the dynamic atomic modeling package currently being developed.

Summary

Simultaneously time- and space-resolved K-shell and L-shell x-ray spectra have been recorded for the first time from laser-irradiated microdot targets. Electron temperatures and densities determined using spectral line ratio techniques have been compared to simultaneous (model independent) measurements and exhibit large differences. These new experiments clearly show the difficulties in analyzing spectral data using standard line intensity ratio techniques due to the highly non-equilibrium ion distribution and line opacity effects characteristic of these laser-produced plasmas. New, non-stationary modeling methods are being developed for both K-shell and L-shell plasmas. Preliminary comparisons of the time- and space-resolved spectral data with atomic and hydrodynamic simulations show some promise but strongly suggest that improvements in the atomic data and/or calculational procedures are necessary.

Acknowledgements

This work was performed in part under the auspices of the U.S. Dept. of Energy by KMS Fusion, Inc. under Contract No. DE-AC08-82-DP40152 and by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References

1. S.R. Stone and J.C. Weisheit, UCID-20262 LLNL (1984); V.A. Boiko, et al, Sov. J. Plasma Phys. 10, 82-86 (1984); R.L. Kauffman, et al, Phys. Rev. A 35 (10), 4286-4294 (1987).
2. M.J. Herbst, et al, Rev. Sci. Instrum. 53 (9), 1418-1422 (1982).
3. Gar.E. Busch, et al, Rev. Sci. Instrum. 56(5), 879-884 (1985).
4. B.K.F. Young, et al, Rev. Sci. Instrum. 57(11), 2729-2732 (1986).

5. B.K.F. Young, et al, Proc. of SPIE, Report No. 831-02 (1987); G. Charatis, et al, IAU No. 102, J. de Physique, (1987).
6. C. DeMichelis and M. Mattioli, Nucl. Fusion 21(6), 677-754 (1984).
7. R.W. Lee, et al, J. Quant. Spectrosc. Radiat. Transf. 31, 91-101 (1984).
8. B.K.F. Young, G. Charatis, Gar. E. Busch, C.J. Cerjan, and R.E. Stewart (to be published).
9. V.A. Boiko, et al, Sov. J. Quant. Electron. 4, 1212(1975).
10. G.B. Zimmerman and W.L. Krueer, Controlled Fusion 2, 51 (1975).
11. D.L. Matthews, et al, Phys. Rev. Lett. 54, 110 (1985); M.D. Rosen, et al, Phys. Rev. Lett. 54, 106 (1985).
12. J. Bailey, et al, J. Phys. B 19, 2639 (1986); J.F. Seely, et al, Phys. Rev. A 34, 2942 (1986).
13. W.H. Goldstein, et al, Phys. Rev. Lett. 58, 2300 (1987).
14. P.L. Hagelstein, UCRL-53100 LLNL (1981).