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Laser-Plasma Weapons-Effects-Simulation Progress Report

**Michael A. Gusinow, David Woodall, John P. Anthes, Merrill A. Palmer,
Eugene J. McGuire, M. Keith Matzen, Kenneth M. Gilbert**

Sandia Laboratories

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LASER-PLASMA WEAPONS-EFFECTS-SIMULATION
PROGRESS REPORT

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INTRODUCTION

The present goal of the Laser-Plasma Weapons-Effects-Simulation Program is the study of the conversion of laser radiation to x-radiation. The purpose is ultimately to make an intense pulsed source of x-rays to be useful in simulation programs. The requirement of a large conversion efficiency (from Laser to x-radiation) is important in order to minimize the energy requirements, size, and expense of the laser system.

The current program is oriented towards doing those experiments (plasma and x-ray studies) that will enable us to develop a code capable of predicting both the plasma and radiation properties of a laser-plasma interaction. An issue of paramount importance in the present context is the question of non-equilibrium processes. It is relatively easy to use the concept of Local Thermodynamic Equilibrium (LTE) to predict certain plasma behavior; however, even with the assumption of LTE, it is difficult at present to calculate the plasma opacity in spectral regions of interest. A problem which must be considered (experimentally and theoretically) is that of plasma opacity under conditions where non-equilibrium processes are important. In terms of a pulsed x-ray source, there appear to be three spectral regions with which one might expect the physics of the radiation production to be different; 1) $\delta < 0.5$ keV. We believe that the study of heavy elements (high Z) is important for this region and we anticipate high fluxes of line radiation. 2) $0.5 < \delta < 5$ keV. In this region, it appears likely that the production of L and M radiation from intermediate Z elements may result in high conversion efficiencies. For example, at present with a Ni target we have measured a 12% conversion efficiency (relative to the incident energy) using a glass laser. 3) $\delta > 5$ keV. The production of an intense source in this region (via laser irradiation) is purely speculative and while some consideration has been given to methods of attacking this issue, it clearly is the most difficult aspect of the overall problem.

I. Nd: Glass Laser

The Sandia Glass Laser System has been reconfigured and a new single mode oscillator has been inserted to provide energetic nanosecond-duration 1.064-micron laser pulses for simulation experiments. The Nd: YAG oscillator¹ uses a Q-switch (a flowing saturable dye cell) to generate nominal 7-nsec bandwidth-limited (< 75 MHz) optical pulses with 0.33 mradians divergence at 1.064 microns. The oscillator output is spatially filtered to ensure far field propagation characteristics. The beam then impinges upon a photographic apodizer² to shape the beam profile, thus minimizing Fresnel diffraction in the glass laser amplifier system. The laser pulse is then directed into a linear string of five Nd:glass laser amplifiers for delivery to the target at a distance of approximately 30 meters from the oscillator. A streak camera investigation of the oscillator output has demonstrated that picosecond structure on the temporal pulse history was absent. A fast photodiode record taken at the output of the amplifier system as shown in Fig. 1 disclosed a triangular pulse with a fast rise and slower fall time. The output pulse asymmetry is thought to be due to gain saturation in the last amplifier. Output energies reaching the target are monitored with a 4% beam splitter and calorimeter just prior to the window of the vacuum chamber. The calorimeters are volume absorbers and are reported to be accurate to within $\pm 1\%$. Pulses containing up to 57 Joules have been utilized to irradiate targets. Reflection of the laser pulse by the target back into the focusing lens is also monitored by a 4% beam splitter and a calorimeter. Reflection is generally less than 7% of the energy incident on the target.

Several experiments were conducted to diagnose the characteristics of the laser beam at the target vacuum chamber. A shear plate interferometer^{2,3} was utilized to determine the wavefront distortion and the divergence of the laser beam. Figure 2 is a photographic interferogram of a laser beam that contained 33.2 Joules. The S shape of the fringes indicates a spherical aberration of about one wave. The fringe tilt of about 57° with respect to the horizontal cursor corresponds to a 1.5 mradians beam divergence. The focal spot of the laser using a F/4.5 aspheric corrected lens was examined by recording the percentage transmission of the laser pulse through a pinhole of known diameter.^{2,4} With a 50- μ m-diameter pinhole, a maximum transmission of $66\% \pm 4\%$ of the incident laser energy was propagated through the pinhole

Glass Laser Output Pulse

Photodiode Output of Laser Pulse. The sweep speed is 5 nsec/major division.

FIGURE 1

Shear Plate Interferogram of Glass Laser Output

Shear Plate Record of a 33.2 Joule laser pulse (time Integrated).

FIGURE 2

For a target shot containing 35 Joules in 7 nsec, this focal spot size corresponds to a laser flux of about 2.7×10^{14} W/cm².

Other laser parameters that were investigated were the amount of amplified spontaneous emission (A.S.E.) and the polarization of the beam at the entrance to the experimental vacuum chamber. Approximately 300 μ J of A.S.E. delivered over about 150 μ sec time duration reached the vacuum chamber prior to the arrival of the main laser pulse. Effects of this small amount of A.S.E. on the laser absorption by the target plasma are unknown. When a dielectric polarizer was placed near the vacuum chamber and set to transmit P polarization (defined relative to the target normal-laser beam plane) about 27% of the incident beam was rejected by the polarizer. The polarizer was left in place for all target studies. The extinction ratio for typical dielectric polarizers is about 100:1.

II. X-Ray Diagnostics

The x-ray diagnostics consists of three instruments (all time integrations): A) a bent (convex) crystal spectrograph, B) a 22-channel K-edge filter spectrometer, and C) an x-ray pinhole camera. Table I summarizes the energy bandwidths of these devices. A XRD (x-ray diode) will be installed soon.

TABLE I	
<u>Instrument</u>	<u>Energy Range</u>
Crystal Spectrograph	0.7-4 keV
K-edge filter spectrometer	0.5-30 keV
XRD	Near uv-1 keV
Pinhole Camera	0.7-4 keV

A) Crystal Spectrograph

A convex bent crystal spectrograph has been utilized to determine the spectrum (line and continuum) of radiation by the laser-produced plasma in the x-ray region. The spectrograph uses a bent KAP crystal (.005 cm thick) with a 2.2 cm radius of curvature to diffract x-rays according to the Bragg condition, $n\lambda = 2d \sin \theta$. The 2d spacing for KAP is 26.64 Å. The spectrograph is operated within the target chamber and is located 11 cm from the

Experimental and Predicted L-series X-Ray Spectrum for Various Stages of Ni Ionization ($Z \leq 27$)

- A. Theoretical L. M. lines from various Ni ionization stages.
- B. Spectrograph of a plasma produced from a Ni target.

Ni target 34.6 Joules on target

(A)

Figure 3

TABLE II
One Electron Binding Energies for Nickel Ions
Calculated with the Herman - Skillman Atomic Structure Code

Net Charge	E(1s) (Ry)	E(2s) (Ry)	E(2p) (Ry)	E(3s) (Ry)	E(3p) (Ry)	E(3d) (Ry)
0	-607.7	-72.97	-63.86	-8.500	-5.756	-1.115
1	-603.88	-72.714	-64.008	-8.7160	-5.9814	-1.3871
2	-605.26	-74.128	-65.419	-10.059	-7.3129	-2.6599
3	-606.91	-75.826	-67.113	-11.619	-8.8593	-4.1509
4	-608.80	-77.771	-69.056	-13.354	-10.578	-5.8254
5	-610.92	-79.939	-71.222	-15.233	-12.442	-7.6606
6	-613.23	-82.311	-73.595	-17.239	-14.435	-9.6423
7	-615.74	-84.877	-76.165	-19.359	-16.544	-11.761
8	-618.42	-87.627	-78.924	-21.585	-18.764	-14.009
9	-621.33	-90.556	-81.863	-23.906	-21.085	-16.379
10	-624.39	-93.654	-84.979	-26.323	-23.562	-18.76
11	-627.83	-96.766	-88.142	-28.749	-25.938	-21.22
12	-631.41	-99.980	-91.413	-31.227	-28.430	-23.71
13	-635.13	-103.290	-94.787	-33.758	-30.976	-26.40
14	-638.97	-106.701	-98.267	-36.323	-33.571	-29.11
15	-642.95	-110.205	-101.846	-38.936	-36.214	-31.96
16	-647.05	-113.799	-105.521	-41.601	-38.92	-34.96
17	-651.08	-117.369	-109.160	-44.444	-41.68	-38.13
18	-655.27	-121.11	-112.95	-47.42	-44.63	-41.54
19	-659.86	-125.36	-120.79	-50.62	-47.89	-45.26
20	-676.74	-135.73	-128.79	-54.03	-51.37	-49.36
21	-687.91	-143.23	-136.94	-57.71	-55.17	-53.96
22	-699.36	-150.84	-145.20	-61.70	-59.49	-58.78
23	-711.06	-158.53	-153.56	-66.05	-64.39	-64.00
24	-722.98	-166.31	-162.69	-70.71	-69.44	-69.44
25	-733.67	-174.53	-173.13	-75.77	-75.11	-75.11
26	-747.10	-184.83	-183.90	-81.22	-81.00	-81.00

x-ray source. It is light-tight but not vacuum tight. X-rays enter the spectrograph through a 1.6-cm-diameter aperture covered with a window of $130 \mu\text{g}/\text{cm}^2 \text{ Al} + 40 \text{ m g}/\text{cm}^2 \text{ C}$ and then impinge upon the bent KAP crystal (the plasma has an approximate diameter of $100 \mu\text{m}$ and acts as the effective input slit). The diffracted x-rays are recorded on 1.27-cm-wide Kodak 3490 film which is captured in a 5-cm-radius arc. An externally activated electronic film transport allows 20 spectra to be recorded before breaking the chamber vacuum to process the film. Additional details concerning spectrograph designs, dispersion relationships, resolution, and line shapes for cured crystal spectrographs are discussed in Ref. 5.

Figure 3b is an L x-ray spectrum obtained from a laser produced Ni plasma. The two lines at the left are L_{α} and L_{β} x-rays from Ni while the line distribution observed to the right correspond to radiation from multi-ionized states of Ni.

As a first cut in relating the measured L-M x-ray spectrum obtained from a laser-produced plasma to the temperature and ion distribution, we have obtained Herman-Skillman eigenvalues for ground state ions in all stages of ionization. It is assumed that the $L_{2,3}$ spin orbit splitting remains the same for all stages of ionization (17eV). As this is a first cut, term-splitting within a configuration, i.e., multiplet effects, have been neglected. If the experimental resolution warrants it, the multiplet effects can be included later. In Table II the Herman-Skillman eigenvalues are listed. Entries above the jagged line were obtained from the Herman-Skillman calculations, while those below the jagged line were obtained from extrapolated effective principal quantum numbers. For the L_3 level we use $E = E_{\text{HS}} + 17/3$, and for the L_2 , $E = E_{\text{HS}} - 2 \times 17/3$, in determining the energy positions of the various L-M lines.

For those transitions where Auger decay is possible the fluorescence yield has been calculated. The Auger yield is determined by using neutral nickel Auger matrix elements, and the procedure described by Larkins.⁸ For example, for N_1^{+0} to N_1^{+9} we use

$$A(L_3) = 2\pi [A(3s,3s) + A(3s,3p) + A(3p,3p) + \frac{n}{10} A(3s,3d) + A(3p,3d) + \frac{(n)(n-1)}{90} A(3d,3d)] \quad (1)$$

where n is the number of 3d electrons in the ion.

We have included Coster-Kronig decay of the L_1 ($L_1-L_{2,3}M$) but have not included super Coster-Kronig decay of M_1 or $M_{2,3}$ vacancies. The latter occur for, at most, the first 4 ion stages. In Table III the calculated energy and fluorescence yield are listed for transitions involving an inner-shell hole. In Fig. 3a we plot the position of all the L-M lines arising from either a 2s or 2p vacancy.

For highly stripped ions one cannot a priori assign fluorescence yields. For example in Ni^{+10} there are no 3d electrons in the groundstate, but in a laser produced plasma there can be $L_{23} - M_{4,5}$ radiation since energetic electrons can cause the $(2p)^6(3s)^2(3p)^6 \rightarrow (2p)^5(3s)^2(3p)^6(3d)$ transition. The upper level can decay via $L_{23} - M_{4,5}$ emission. For these cases we estimate the energy position of these transitions. The results are also shown in Fig. 3a.

A comparison between Figs. 3a and 3b indicates that there is consistency between the experimental results and the predictions of theory as to the identification (in a semi-quantitative sense) of the spectrum from the Ni plasma. Note that the spectra disappears for $E > 1.4$ keV indicating very high stages of ionization. This is in agreement with ion diagnostics and calculations to be presented later in this report.

While the present calculations have been done for nickel, it is a straightforward procedure to make the computations for every element of interest.

B) K-Edge Filter Spectrometer

The use of K-edge filter spectrometers in conjunction with a variety of detectors for diagnosing x-ray spectra from high temperature plasmas has been previously reported.⁹⁻¹² A number of factors combine to make this type of spectrometer a very useful instrument for studying x-ray emission from laser-produced plasmas. First, the x-ray spectra from these relatively hot plasmas will consist primarily of continuum spectra resulting from free-free and free-bound radiation. Thus, K-edge filters which for most materials have well-characterized cross sections, together, for example, with the known PIN diode response, provide sufficient resolution for determining the spectrum. (See the Appendix for a discussion of using K-edge versus Continuous filters). Second, the radiation from laser-produced plasmas is typically intense enough to produce a large signal from the silicon PIN diodes. Third, these diodes exhibit long-term stability and less than 10%

TABLE III
Energy Position and Fluorescence Yield (W) of Inner-Shell L-M Radiative Transitions for Ni Ions

Net Charge	L_3^- E(ev)	$M_{4,5}$ W	L_2^- E(ev)	M_4 W	L_3^- E(ev)	M_1 W	L_2^- E(ev)	M_1 W	L_1^- E(ev)	$M_{2,3}$ W
0	847.7	.0074	864.7	.0074	747.2	.00037	764.2	.00039	908.7	.00038
1	846.0	.0075	863.0	.0075	746.3	.00042	763.3	.00042	907.6	.00049
2	847.9	.0075	864.9	.0075	747.2	.00047	764.2	.00047	908.7	.00054
3	850.6	.0075	867.6	.0075	749.0	.00053	766.0	.00053	910.8	.00083
4	854.3	.0073	871.3	.0073	751.9	.00060	768.9	.00060	913.8	.00097
5	858.8	.0070	875.8	.0070	755.8	.00069	772.8	.00069	918.0	.00213
6	864.1	.0065	881.1	.0065	760.8	.00081	777.8	.00081	923.1	.0139
7	870.2	.0056	887.2	.0056	766.9	.00092	783.9	.00092	929.3	.0156
8	877.2	.0043	894.2	.0043	774.1	.0011	791.1	.0011	936.5	.0176
9	884.9	.0025	901.9	.0025	782.5	.0012	799.5	.0012	944.8	.0198
10					792.1	.0014	809.1	.0014	954.1	.0222
11					802.1	.0020	819.1	.0020	963.3	.0265
12					812.9	.0032	829.9	.0032	973.1	.0323
13					824.4	.0056	841.4	.0056	983.5	.0410
14					836.6	.0118	853.8	.0118	994.6	.0553
15					849.9	.0357	866.9	.0357	1006.3	.0819
16					863.6	.135	880.6	.135		
17					878.5	1.00	891.5	1.00		

For neutral Ni experimental values are:

$$E(L_1-M_{23}) = 942. ; E(L_2-M_1) = 762. ; E(L_2-M_{44}) = 868.8$$

$$E(L_3-M_1) = 742.7 ; E(L_3-M_{45}) = 851.5$$

detector-to-detector variation in response to a given spectrum. Finally, without calibrating each detector, the absorption properties of silicon are well enough known, and the manufacturer's specifications are sufficiently accurate that a spectral unfold based on K-edge filtered signals from PIN detectors is essentially an absolute spectrum. Only the areas under the signals which correspond to the total charge liberated in the detector are utilized in the analysis. The 10 nsec response time of the PIN detectors is inadequate to time-resolve the plasma x-ray pulse. The XRDs are not so limited.

The choice of K-edge filters is dependent on the energy range of interest with the K-edge energy of a given material being an index of the energy where it is most effective. Typically, one chooses filters whose thickness is three mean paths at the K-edge energy, above the K edge. However, there are significant parts of the x-ray spectrum which are inaccessible to the K-edge filter technique because foils are not available, cannot be obtained pinhole-free, are too reactive to use, or not practical to fabricate. In these regions, one uses varying thickness foils of "practical" materials which border the inaccessible region.

The analysis of the spectrometer data is dependent on a detailed description of the filter-detector response. Figure 4 schematically depicts a single K-edge spectrometer channel. It shows the K-edge filter and the detector which can be characterized as consisting of a dead layer and an active or depletion region. The charge output Q_1 of such a channel when irradiated with an x-ray energy spectrum $S(E)$ is given by the following integral equation:

$$Q_1 = AB \int_{\text{all } E} R_1(E) S(E) dE, \quad (2)$$

Where A is the detector area exposed to x-rays, B is the detector sensitivity of 0.272 C/J of energy absorbed in the depletion region and the response function $R_1(E)$ for the its channel is given by

$$R_1(E) = e^{-\eta_1(E) \rho_1 X_1} - \mu_2(E) \rho_2 X_2 \left[\frac{\mu_2(E)}{\eta_2(E)} \left(1 - e^{-\eta_2(E) \rho_2 X_3} \right) \right] \quad (3)$$

The K-edge filter, dead layer, and depletion layer elements are identified by the subscripts 1, 2 and 3, respectively. The attenuation coefficient η denotes the total mass attenuation coefficient. The attenuation coefficient μ

ELECTRICAL CIRCUIT FOR K-EDGE DETECTOR

Schematic of a single channel of the K-edge filter PIN diode spectrometer.

FIGURE 4

denotes the energy transfer coefficient which ignores the energy carried off by Compton scattered photons. The mass density is ρ , X_j is the thickness of the j th element, ($j = 1, 2, 3$) and E is the photon energy. Physically, the product of the first two exponential terms gives the fraction of the incident spectrum transmitted through the K-edge filter and dead layer. The bracketed term gives the fraction absorbed in the active region. By choosing K-edge filters with K-edge energies as uniformly spaced as possible over the spectral region of interest, one then has a number of cuts of the spectrum determined by the respective response functions. The spectrum $S(E)$ is obtained by inserting the experimental values Q_i and the response functions $R_i(E)$ into Eq. (1), and solving the resulting integral equations for $S(E)$. The iterative unfold code, SLAM¹³ was used.

A typical result is shown in Fig. 5. The temperature (450 ± 30 eV) determined from the bremsstrahlung radiation in the vicinity of approximately 2-6 keV is a color temperature and is expected to represent the peak plasma electron temperature. The energy spectrum consists of a 450 eV bremsstrahlung distribution superposed with unresolved Ni L-radiation centered about 1 keV. It is to be noted that if one extrapolates the bremsstrahlung radiation in the region 2-6 keV to the 1 keV energy that the L radiation is approximately a factor of 20 times greater than the bremsstrahlung. This is consistent with the results of the bent crystal spectrograph (Fig. 3a). The conversion efficiency of 12% was obtained assuming isotropic emission into 2π steradians.

C) X-Ray Pinhole Photographs

X-ray pinhole pictures were obtained for most of the target materials. A complete description of the particular x-ray pinhole camera used, its design and performance, has been published.¹⁴ Briefly, the camera is useful over a range of x-ray energies determined by its aperture, window, and the film characteristics which in this application was approximately 1 keV to 3 keV. The camera utilized a pinhole array which permitted several simultaneous exposures at unity magnification covering a range of exposure and resolution according to individual aperture size. Pinhole diameters of 2 μm , 5 μm , 10 μm , 20 μm , and 50 μm gave, to a first approximation, a circular resolution element at the film plane equal to twice the respective pinhole diameter. Kodak No-Screen Medical X-ray film was used. In this application, it exhibited a useful exposure range of ~ 60 . The photographic images were digitized with a

X-Ray Spectrum at 1cm From the Source

The "unfolded" spectrum radiated by a Ni plasma.

Photometric Data System Model 1010 microdensitometer. The digitized data on magnetic tape served as input to the CDC 6600 computer system for image processing and two-dimensional data graphic output from the program IMAGEN.¹⁵ The photographic data, in terms of optical density, have been corrected for film response and are presented in terms of relative exposure in Figs. 6 through 9. In this regard, it was necessary to determine the effective optical density for Kodak No-Screen film for the microdensitometer numerical aperture of 0.25 relative to diffuse density values published by the manufacturer and others.^{16,17}

For the 50 μm pinhole data shown in Figs. 6 and 7, the most exposed part of the photographic image was saturated, i.e., the mixture density on film exceeded the density reading capability of the microdensitometer. This occurs at a density value of approximately 5.0. As a result, a FWHM diameter based upon the data presented in Fig. 6 and corrected for pinhole resolution will be too large. For the 10 μm pinhole photograph, the entire image is below saturation density, and the FWHM diameter determined in this manner from the data presented in Fig. 8 is $\sim 140 \mu\text{m}$. Microdensitometer scanning parameters resulted in a square picture resolution element $16 \mu\text{m} \times 16 \mu\text{m}$ for Figs. 6 - 8 and $8 \mu\text{m} \times 8 \mu\text{m}$ for Fig. 9. In all cases, this resolution was smaller than the pinhole resolution as indicated in the Figures.

III. Plasma Ion Measurements

In addition to extensive measurements of the x-ray emission of hot laser-produced plasmas, simultaneous measurements are made of the ions emanating from the plasma region. Under the appropriate conditions it is possible to draw inferences about the plasma. It is also important to ascertain the importance of plasma acceleration due to electrostatic potentials set up during the plasma expansion. At present, the diagnostics consists of a Thomson parabola and a magnetic ion spectrometer. The vacuum in the target chamber is typically 10^{-6} Torr. A relatively high vacuum is required to obtain unambiguous results from the ion diagnostics.

A. Thomson Parabola

The operation of the Thomson parabola ion analyzer has been described in Ref. 18. It consists of transmitting the plasma ions through an analyzer region in which there exists parallel electric and magnetic fields transverse

Iso-exposure contours from 50 μ m diameter pinhole photographs.

○ Pinhole dependent resolution element.

□ Microdensitometer sampling resolution element.

FIGURE 6

Computer generated image from 10 μm diameter pinhole photograph.
Resolution elements indicated as in Figure 6 caption.

FIGURE 7

Iso-exposed contours from 10 μ m diameter pinhole photograph.
 Resolution elements indicated as in Figure 6 caption.

FIGURE 8

Computer generated image from 90 μm diameter pinhole photograph.
Resolution elements indicated as in Figure 6 caption.

FIGURE 9

to the direction of motion of the impinging ions. The coordinate system used in the present work is shown in Fig. 10. Note that each A/Z state (A is the atomic mass and Z the charge state of the ion) exhibits a parabolic trace and that ion energy decreases with increasing distance from the origin. Figure 11 is illustrative of the differences in the expanding plasma for two elements having considerably different atomic masses (and hence atomic numbers). The two photographs pertain to different laser energies but even at the same energies, one observes many levels of ionization for relatively heavy elements while in the case of Be, for example, one sees all states, i.e., the Be has been completely stripped. Figure 12 is data taken from the same shots of Figs. 3 and 5. Notice the width of the parabola traces as compared to those in Fig. 11. The wider traces are due to isotopes of Ni present in the target.

B. Magnetic Ion Spectrometer

The magnetic ion spectrometer uses a 1.6 kG transverse magnetic field to separate ions of different momenta. Seven detectors (charge collecting plates) record the arrival of ions with gyro-radii of 17-250 mm. This corresponds to hydrogen ions with energies from 0.4-80 keV. The charge collected by the detectors is amplified by preamplifiers and the resulting signals recorded on oscilloscopes. This device has the advantage over the Thomson parabola of retaining time-resolution. On the other hand it has the disadvantages of requiring detailed unfolding of the data in order to obtain ion spectra and having a much lower A/Z resolution than the Thomson parabola. Using time-of-flight computations (probably valid for the present work), the ions arriving at a particular detector have arrival times which scale as $t_H (A/Z)$ where t_H is the proton arrival time, A is the ion atomic mass, and Z is the ion charge state. The energy scaling on the same detector is $E_H (Z^2/A)$ where E_H is the proton energy. For light target elements (low Z), the ion signals are well separated in time and an unambiguous analysis is possible. However, for heavier elements the signals of different charge states overlap on the individual detectors, thus requiring a complicated unfolding procedure in order to obtain ion spectra. Another complication in obtaining the ion spectrum arises from the abundance of various stages of isotopes in some of the target materials.

An example of ion spectra is shown in Fig. 13. This particular spectrum is time-integrated and thus should be comparable to the Thomson parabola data from the same shot. In this particular series of experiments, the Thomson

B - MAGNETIC FIELD IN GAUSS
 Z - ION CHARGE STATE
 E - ION KINETIC ENERGY (keV)
 A - ION ATOMIC MASS
 V - VOLTAGE ACROSS FIELD PLATES

The coordinate system used for analysis of the ion traces observed at the analyzer exit face.

FIGURE 10

Thomson Parabola Ion Diagnostics of Laser Produced Plasmas

Be target

10.77 Joules on target
Deflection plate voltage:
 $V = 52$ volts

Magnetic field:
 $B = 122.6$ Gauss

In target

34.17 Joules on target
Deflection plate voltage:
 $V = 122$ volts

Magnetic field:
 $B = 277.2$ Gauss

Thomson parabola traces for Be and In laser-produced plasmas.

FIGURE 11

Thomson Parabola Diagnostic

Ni target 34.6 Joules laser energy on target

Deflection plate voltage:

$V = 40$ volts

Magnetic field:

$B = 187$ Gauss

A Thomson parabola trace for a Ni laser-produced plasma.

FIGURE 12

parabola and ion spectrograph were viewing the plasma at considerably different angles and consequently one might expect some differences in results if the plasma is expanding anisotropically. (Experimental evidence obtained with two Thomson parabolas at different angles substantiates this view.) Figure 14 shows the Thomson parabola data for this particular Be shot. Note the absence of Be^{+1} and the relative abundances of Be^{+2} , Be^{+3} , and Be^{+4} (the brightness of the traces is taken as a measure of relative abundance). The quantities of Be^{+2} , and Be^{+3} , do not agree with Fig. 13. The lowest energies shown on Fig. 14 are 24, 13.5 and 6.4 keV for $z = 4, 3$, and 2 . The straight line on Fig. 14 through the origin corresponds to a constant energy of 34.3 keV for all the charge states. Referring to Fig. 13 it is seen that at this energy there is a considerable difference between the two diagnostics. Presently, we have no quantitative evidence as to the cause of the difference but believe it to be due to anisotropic plasma expansion. The cutoff energies as measured by those portions of the traces near the origin indicate cutoff energies for $Z = 4, 3$, and 2 of 162, 130 and 64 keV respectively. The highest energies observed for these charge states with the ion spectrograph were 500, 90, and 40 keV respectively.

IV. Target Absorption Measurements Using an Integrating Sphere

Understanding the absorption of laser radiation by a target plasma environment is of basic importance to the present experiments. Absorption may be determined by measuring the energy reflected from the target relative to the total incident energy. By deduction, the remainder represents the absorbed energy. Use of an integrating sphere in this application has been reported by Godwin, et al.,¹⁹ and we plan to apply this technique.

A 15-cm diameter integrating sphere coated on the inside with Eastman 6080 white reflectance coating, has been designed to accommodate a planar target as shown in Fig. 15. Two PIN diode detectors, spectrally limited with narrow bandpass interference filters, permit measurements of both $1.06 \mu\text{m}$ radiation. Appropriate baffles are included to shield the detectors from any direct radiation. The initial measurements will be carried out for a 17° angle of incidence to the target normal. Because the detector signal is independent of angular distribution, the response equivalent for 100 percent reflectance may be obtained by irradiating the sphere with the Nd:glass

The time integrated ion energy spectrum for a Be plasma.

FIGURE 13

Thomson Parabola Diagnostic

Be target 6.93 Joules laser energy on target

Deflection plate voltage:

$V = 40$ volts

Magnetic field:

$B = 277.2$ Gauss

A Thomson parabola trace for a Be laser-produced plasma.

FIGURE 14

INTEGRATING SPHERE

A schematic representation of the integrating sphere to be used for laser absorption measurements.

FIGURE 15

pulsed laser system at known energy, but with the target removed. Energy back-reflected through the focusing lens is a quantity which must be included in the total reflected energy measurement.

This measurement technique is also planned for HF laser target experiments using a similar sphere assembly with the exception that the inside surface coating is diffuse gold for high efficiency at HF laser wavelengths.

V. Laser-Plasma Modeling

The theoretical effort has emphasized the development of computer codes to model the laser-produced plasmas. Through this modeling we have gained insight into important mechanisms involved in our current planar target experiments and ultimately hope to use these models to design targets that maximize the x-ray conversion efficiency. The modeling has involved work in two major areas. First, a one-dimensional Lagrangian hydrodynamics code has been used to study the absorption of the laser energy and the subsequent plasma expansion characteristics. Second, a plasma kinetics code has been developed to study nonequilibrium processes in the laser-produced plasma. Presently these codes are being developed separately, although future work will require that they be coupled together for accurate modeling.

The hydrodynamics code that we are using is a form of CHAMISA,²⁰ which has been modified to include tabular equations of state²¹ and more realistic laser absorption packages and specialized to handle laser-plasma related problems. A single-fluid two-temperature one-dimensional Lagrangian code of this type assumes that the grid points move with the fluid. With each grid point is an associated position, inertial mass, velocity, and area. Between each pair of grid points we define a volume, thermodynamic mass, density, and thermodynamic properties such as temperature, pressure, internal energy, heat capacity, and emissivity for both electrons and ions. The equations involved in solving for the hydrodynamic motion of the plasma may be simply expressed as an equation of motion,

$$\dot{v}(\underline{r}, t) = - \frac{1}{\rho(\underline{r}, t)} \nabla [P(\underline{r}, t)], \quad (4)$$

a conservation of energy equation for electrons

$$\rho C_{ve} \dot{T}_e = \dot{Q} - T_e \left(\frac{\partial P_e}{\partial T} \right) \dot{v}, \quad (5)$$

and a similar energy conservation equation for ions. In these equations v is the velocity of a grid point and ρ , P , C_v , T , V , and Q are the thermodynamic density, pressure, specific heat, temperature, volume, and heat transfer rate, respectively. In the present version of the code, the heat transfer rate includes the deposition of the laser energy, diffusion of heat between the grid points, radiation heat loss from bremsstrahlung and recombination, and a heat exchange between the electrons and ions.

To compare the code calculations with the results from the present thick foil experiments, the code was run in its spherical geometry option. For the comparisons reported here, the spherical radius was chosen to be $50\text{ }\mu\text{m}$ and the laser energy was absorbed via inverse bremsstrahlung and resonance absorption. In Figs. 16, 17, and 18 we show the velocity, density, and temperature profiles at a time (10.2 ns) near the peak power of an 8 ns FWHM irradiation of a Ni target with 35 J focused to a $100\text{ }\mu\text{m}$ diameter spot. The tendency to set up a very sharp density gradient and a resulting series of fluid points with relatively constant velocity is characteristic of an ablatively driven target.²² In this particular case, the ablation velocity of $4.6 \times 10^7\text{ cm/s}$ compares quite well with the experimentally observed cutoff velocity in the Thomson parabola (Fig. 12) of $4.3 \times 10^7\text{ cm/s}$. An even more striking comparison occurs with the electron temperature. The calculations show a time averaged maximum electron temperature of 530 eV at the critical surface whereas the x-ray unfold yields an electron temperature of 450 eV (Fig. 5). During the time of the peak laser intensity, the calculation gives a plasma "diameter" (defined by the location of the critical surface) of $120\text{ }\mu\text{m}$. This is to be compared to the pinhole result (Fig. 8) of $140\text{ }\mu\text{m}$. The assumption that the x-rays arise predominantly from a volume contained within the critical surface.

We emphasize that these comparisons are from a "first attempt" i.e., in the jargon of present day plasma physics, there was no knob turning. The laser energy deposition, heat transfer, and radiation loss packages were all run with parameters determined by simple, first principle considerations. The laser energy deposition (simple inverse bremsstrahlung plus resonance absorption) is believed to be a fairly accurate description of the absorption mechanism. The flux limit value in the heat transfer rates was set to its classical value of 0.6. The most serious problem in these calculations is the radiation loss package. It is assumed that only bremsstrahlung and radiative recombination contribute to the radiative losses and that the plasma

The velocity profile of the zones of a Ni target at a time (10.2 ns) near the peak power of an 8 ns FWHM, 35 J Nd: glass laser pulse focused to a 100 μm diameter spot.

FIGURE 16

The density profile corresponding to Figure 16.

FIGURE 17

The electron (x) and ion (o) temperature profiles corresponding to Figure 16.

FIGURE 18

is thin to this radiation. The experimental data strongly indicates the importance of line radiation and it is highly unlikely that the plasma is thin. Work is in progress to improve the radiation package.

The second area of concentration involves the study of nonequilibrium processes in the high density and expanding plasmas. To examine these effects a plasma kinetics code has been developed which runs either concurrently with or as a post-processor to the hydrodynamics code. The coupled rate equations presently describe only the densities of the various ionization stages and retain no information about the excited electronic states of the individual ionization stages. These rate equations are coupled to the Lagrangian hydrodynamics code through the temperature and density of each Lagrangian zone. For these temperature-density parameterizations, the ion species density distributions may be found either by time integrating the coupled rate equations or by solving the homogeneous rate equations for the steady-state solutions. An illustration of the time dependent effects which can occur in a Lagrangian zone are shown in Fig. 19. Here a 50 ps Nd:glass pulse was incident on a planar carbon target such that the peak power was $3 \times 10^{13} \text{ W/cm}^2$. The time history of the laser intensity (I), electron temperature (T_e) and ion density (N_i) are shown. The differences between the time-integrated (solid curve) average ionization stage, $\bar{Z}$, and the rate equation steady state $\bar{Z}$ (dash-dot curve) are caused by the finite time required for both ionization and recombination processes. The difference between the rate equation steady state $\bar{Z}$ and Saha equilibrium $\bar{Z}$ (dash curve) arises because of the inclusion of radiative recombination in the rate equations. Given the ion distributions for each Lagrangian zone, ion detector traces (Thomson parabolas, for example) can be constructed.

The x-ray emission is also dependent on the ionization stages present in the plasma. An indication of the importance of properly considering time dependent effects may be obtained by considering simple formula for the bremsstrahlung and recombination radiation.²³ In Fig. 20 we show the total x-ray emission from a single zone in an Al plasma created by focusing a 50 ps pulse so that the peak intensity is $3 \times 10^{13} \text{ W/cm}^2$. The time dependent (solid curve) and steady state (dash-dot curve) calculations are seen to differ by a factor of between 2 and 3. These numbers indicate that a more detailed analysis including line emission and opacities should be included in our future work.

The average ionization stage, $\bar{Z}$, for the time dependent rate equations (-), rate equation steady state (-.-), and Saha equilibrium (---) for the Lagrangian zone with the electron temperature shape (T_e , where $T_e(\text{max}) \sim 300 \text{ eV}$) and ion density (N_i) produced by input laser intensity shape (I). The leading surface of this zone was initially $0.01 \mu\text{m}$ from the target surface and the peak intensity was $3 \times 10^{13} \text{ W/cm}^2$.

FIGURE 19

FIGURE 20

The total x-ray emission for a source in an Al plasma which is heated by a 50 ps pulse focused to $3 \times 10^{13} \text{ W/cm}^2$. Time dependent (-) and steady state (-.-) rate equation calculations are shown.

The ionization and recombination rates in the plasma kinetics code are based on either semi-empirical fits to data for low Z elements, or elementary (scaled hydrogenic) calculations. For high Z materials $Z \geq 60$, these approximate rates are likely to be invalid, particularly for $4f$ electron subshells. Preliminary calculations indicate that for the $4f$ subshell the electron ionization cross-section per electron is low and broad when compared to other subshells of comparable ionization energy. The results for neutral tungsten ($Z=74$) are shown in Fig. 21. Note that while the $4f$ subshell has 14 electrons and an ionization potential of only 2.6 Ry., the peak cross-section (at 300 eV) is smaller than that for the $5p$ shell with only 6 electrons and an ionization potential of 3.6 Ry. Currently $4f$ sub-shell electron excitation rates are being examined to determine if they can be large and broad. If the $4f$ excitation rate is large and broad, and the fluorescence yield is close to unity, then: (1) the $4f$ subshell may present a barrier to the production of high stages of ionization in high Z elements, and on the other hand (2) may lead to the efficient transformation of laser energy to soft x-rays, if most of the laser energy is used to excite the $4f$ subshell.

In summary, the hydrodynamics code has demonstrated the capability to give good agreement with experimental results. Fundamental features of both particle and x-ray emission can be modeled. The detailed kinetics code appears to be essential for doing more detailed comparisons with ion and x-ray diagnostics. Therefore, our future work will concentrate upon adding a more realistic radiation package to the hydrodynamic code, adding more detail to the kinetics code and extending the range of materials to which it can be applied, and examining methods of integrally coupling the two codes together.

Conclusion

The diagnostics presently incorporated into this project are all working well. For the most part, they produce consistent results and where differences occur it is believed that these differences are qualitatively understood. The agreement with model calculations is excellent and lends considerable credibility to the ultimate predictability of the calculations.

ELECTRON IONIZATION OF W(Z=74)

Calculated total and subshell electron ionization cross-section for Tungsten (W).

FIGURE 21

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APPENDIX

The K-edge filter technique has been utilized extensively in the spectral analysis of x-rays from laser produced plasmas. Ideally, the sensitivity function for a filter-detector combination will be responsive just below the K-edge energy of the filter where the discontinuity in the absorption coefficient of the filter provides a "spectral notch" from the $e^{-\mu x}$ transmission factor. In the discussion which follows, however, the influence of the spectral shape to be measured on the sensitivity region for a titanium filter-Si-PIN detector combination will be shown. Figure 22 illustrates three spectral shapes and the corresponding sensitivity functions to be considered. For a 500eV Bremsstrahlung spectrum, Fig. 22A shows that the response function peaks at 3keV which is well below the K-edge energy of 4.966keV for titanium. Furthermore, there is no significant spectral response above the titanium K-edge. For a Bremsstrahlung distribution with a temperature even lower than the 500eV shown here, the sensitivity function becomes more responsive to the $1/E^3$ nature of the absorption coefficient and consequently will be shifted even more to the left of the Ti K-edge. In this case the filter no longer can be designated a K-edge filter since the filter thickness and the spectral shape are the determining factors in forming the response function.

In the second example, Fig. 22B, the input spectrum is a linearly decreasing function of energy. The response function here exhibits spectral sampling above as well as below the Ti K-edge. In the third case, Fig. 22C a flat input spectrum yields a response function that samples energy predominantly above the Ti edge. This latter effect becomes even more pronounced for spectra that are increasing functions of energy.

Thus, the utilization of a K-edge filter does not necessarily imply that a filter-detector sensitivity is near the filters K-edge energy, but rather its peak sensitivity region is influenced substantially by the spectral shape to be measured.

**TITANIUM FILTER-SI-PIN DETECTOR RESPONSE AS
A FUNCTION OF SPECTRAL INPUT**

The dependence of the response function on the spectral input for a titanium filter Si-PIN detector. **FIGURE 22**

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