Abstract—We present measurements of the X-ray emission characteristics of laser-irradiated flashlamp foils which are candidates to produce by resonant photoexcitation a population inversion in either a neon or fluorine lasant gas. Using the Shiva 1.06 μm laser, we heated Fe, Cr, and Ni foils to study the brightness and centroid energies of X-ray lines stemming from L–M transitions. Results indicate that appropriately bright and uniform sources can be produced.

I. INTRODUCTION

OVER the past two decades, a wide variety of schemes have been proposed to generate lasing action in the soft X-ray region of the spectrum (20 < hv < 200 eV). For a complete description of many of these schemes, see review papers by Waynant and Elton [1] and Elton [2]. Our work focuses on schemes which can be pumped using an Nd:glass laser. In fact, Hagelstein [3] has performed detailed computer modeling for a variety of Nd:glass laser-pumped soft X-ray laser schemes. Because of the considerable gain (α = 20–50 cm⁻¹) he computes, one particular scheme has captured our attention. The method is to use resonantly pumped photoexcitation to produce a population inversion between either n = 4 to n = 3 states (laser output, ~50 eV) or n = 3 to n = 2 states (laser output ~120-150 eV) in He- and H-like neon or fluorine. This concept of resonant photoexcitation was first proposed by Vinogradov et al. [4], then Bhagavatula [5]. They suggested photoexcitation using nearly resonant line pairs; in fact, they listed several coordinates, among which was the sodium-neon pair (Na 2'P- 1's and Ne 4'P- 1's). Using the Shiva 1.06 μm laser, we heated Fe, Cr, and Ni foils to produce the brightness and centroid energies of X-ray lines stemming from L–M transitions. Results indicate that appropriately bright and uniform sources can be produced.

Fig. 1 presents more detail on the method required to achieve a population inversion using resonantly pumped photoexcitation. X-rays produced by a laser-heated flashlamp strip the cold lasant (in this example, neon) gas down to a helium-like state of ionization. For the case of an n = 4 to n = 3 laser, a line near λ = 11.000 Å (within Δλ = ±0.003 Å) must be present in the flashlamp foil X-ray spectrum to resonantly photoexcite helium-like ions from the 1s²(1S₀) ground state to the 1s4p(1P) excited state. Electron collisions will then primarily populate higher angular momentum n = 4 states such as the 1s4d(1D), 1s4f(1F) which are dipole forbidden to relax to the ground state. In addition, the lower state of the X-ray laser, namely the 1s3p(1P) or 1s3d(1D), rapidly decays by dipole emission to the 1s2p(1P) and 1s2s(1S) states. We can therefore obtain a population inversion between the n = 4 and n = 3 states. The n = 3 to n = 2 laser scheme operates in a similar manner except that the n = 3 states are preferentially excited with a well-chosen flashlamp line. Some candidates for flashlamp materials whose X-ray spectrum contains pump lines at energies close to suitable states in He-like neon or fluorine are given in Table I. This is not an exhaustive list (see, for example, [3]), but it does represent those which have received the most attention to date. Note that, except for He-like Na transitions, all of the pump candidates involve L → M transitions from moderate Z (Z = 24–28) ions. A careful experiment to accurately determine these flashlamp line energies has now been done by Burkhalter et al. [6].

The X-ray emission characteristics of the laser-irradiated...
A schematic of the flashlamp target is shown in Fig. 2. It consists of a thin metallic layer (~400 Å thick) deposited on a ~0.5 μm disk of parylene for mechanical strength. Such thin layers of metals were necessary to ensure maximum X-ray brightness since their emissions would be used in transmission to pump a laser cavity. The thickness was also determined to be the most suitable by computer simulations of the laser-plasma interaction. In essence, the thickness coincides with the distance that the ablation (heat) front moves during the laser pulse. The diameter of the foils were ~2 mm. The foils were suspended across a thin (25 μm thick) Mylar hoop that was 3 mm in OD. An alignment aid in the form of a 300 μm diameter ball was included to facilitate centering of all ten Shiva beams. The targets were irradiated either normal to the bottom set of Shiva beams (for absorption measurements) or at an angle of 30° (rotation in θ where θ is the angle relative to the axis of the incident laser beam cluster). The irradiation in the rotated case enabled diagnostics to view both the front and rear sides of the target. The uniformity and composition of the targets was measured by the Materials Measurement Group of Target Fab. The measurements were performed on foils from which the actual flashlamps were cut and thus should adequately represent the targets. Overall uniformity (with resolution of ~100 μm) determined by both light transmission and sputter erosion was measured to be at least 20 percent. Scanning electron Auger spectroscopy was used to measure the axial material profile of the flashlamp. The results of such a measurement on an Fe flashlamp are shown in Fig. 3. As can be seen in the figure, the bulk flashlamp material (350-450 Å) has both a thin hydrocarbon (2-10 Å)
and oxide layer (10-50 Å) layer on the surface. A 5-20 Å thick oxide and hydrocarbon layer is also seen at the parylene substrate interface. The measured low levels of contaminants should not influence the production of flashlamp X-rays (a thick surface layer of oxygen, e.g., could quench the heating of the metal flashlamp material and consequently reduce the conversion of Shiva laser light to X-rays).

B. Flashlamp Diagnostics

The principal diagnostics used in these measurements are illustrated in Fig. 4. The primary measurement was accomplished using time and space integrated crystal spectrographs [8]. The temporal history of X-ray emission was also monitored using the LLNL soft X-ray streak camera [9] coupled to a transmission grating [10]. A Kirkpatrick-Baez (KB) microscope, filtered to look at X-ray energies ~1 keV, measured the uniformity of the time integrated X-ray emission and the filter fluorescer spectrometer recorded the high-energy (hv > 6 keV) X-ray yield. Target absorption was obtained with an array of scattered light 1.064 μm filtered pin diodes. The laser performance was carefully monitored (e.g., total energy in each beam, pulse length (using optical streak cameras), and spatial profile).

C. Irradiation Conditions

The incident laser irradiation conditions are summarized in Table II. For each shot we list target number, thickness of flashlamp materials, angle of target normal with respect to the laser longitudinal axis, the laser pulse widths measured by several different streak cameras, the total incident laser energy on target, and the nominal laser intensity on target for a 1 mm diameter laser spot (the ten lower Shiva beams (beams 1-10) were overlapped to an approximate beam spot diameter of 1000 μm). Peak laser intensities for these experiments are typically 1-2 × 10^14 W/cm² for a pulse length of 100-120 ps.

III. RESULTS

A. Absorption, Suprathermal X-Rays, X-Ray Source Uniformity

Target absorption was measured by an array of 1.064 μm filtered pin diodes as well as incident and backscattered calorimeters. Light absorption is an important quantity which determines the efficiency of conversion of laser light into target heating, which ultimately results in the desired quantity, namely X-ray production. For the absorption measurements, Fe and Fe-Cu disk targets were oriented at normal to the laser beam to facilitate angular integration over the finite pin diode array. The large effective f-number of the Shiva beam clusters (~f/1) and the long laser pulse (τ ~ 100-120 ps) will result in a negligible dependence of the target absorption on angle of incidence (at least for angles ≤30°). Furthermore, we had expected no significant Z dependence for the modest range of target materials covered in the experiments.

A typical scattered light distribution, obtained on shot 81122202, is shown in Fig. 5. The light distribution shows good azimuthal symmetry (i.e., symmetric emission pattern in angle Φ, the angle rotating about the incident laser beam direction), as can be expected with the radial polarization of the Shiva beams. The θ dependence (angle relative to laser beam axis) is strongly peaked in the backscatter direction. The absorption values, obtained by integrating these data over solid angle, are listed in Table III for the two representative absorption shots. Errors in the individual measurements due to both calibration uncertainties and angular integration are also given in Table III. An absorption value of 45 ± 9 percent is thus obtained from the data.

In order to aid in understanding the absorption mechanisms and to estimate the influence of high-energy electrons on the target irradiation, we attempted to measure the high-energy bremsstrahlung X-rays (hv > 6 keV) from the targets using the Shiva filter fluorescer diagnostic. These X-rays are produced by electrons depositing energy deep into the colder (inner) regions of the disk target. Despite the instrument being set at maximum sensitivity, no detectable signal above background was obtained on all but the highest energy (intensity) shot. Estimates of the suprathermal electron temperature from resonance absorption for the irradiation conditions used in the experiments lie in the range of 4-7 keV (this assumes all of the beams add to give peak intensity of ~2 × 10^14 W/cm²). The minimum detector level of the instrument in this energy range is ~3-5 × 10^12 keV/eV - sphere (this is for the 7.7 keV channel).

Thus, if the suprathermal electrons are confined to the high-Z plasma (whose initial thickness is only ~45 percent of the suprathermal electron range) and they lose all of their

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**Fig. 3.** Axial material profile of X-ray laser flashlamp target determined by scanning auger electron microscope.

**Fig. 4.** Experimental setup for flashlamp experiment.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Species</th>
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<td>~2-10Å</td>
<td>CO, CO₂, H₂O, C₄H₄</td>
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<tr>
<td>10-50Å</td>
<td>FeO, Fe₂O₃, Fe₃O₄</td>
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<tr>
<td>~350-450Å</td>
<td>Fe (trace contaminants)</td>
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<tr>
<td>~5-20Å</td>
<td>FeO, Fe₂O₃, Fe₃O₄, CO, CO₂, H₂O</td>
</tr>
<tr>
<td>5000Å</td>
<td>C₂H₄ (substrate)</td>
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TABLE II
X-RAY LASER FLASHLAMP INCIDENT CONDITIONS SUMMARY

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<th>Shot #</th>
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<th>#</th>
<th>Z</th>
<th>(\Delta t)</th>
<th>(\theta)</th>
<th>(\tau_{in}) (ps, FWHM)</th>
<th>(\tau_{tot}) (ps, FWHM)</th>
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<th>(E_L^0(1))</th>
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<td>0.5 CH</td>
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<td>123</td>
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<td>262</td>
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\(a\)Input streak camera.  
\(b\)Streak camera on beam 6.  
\(c\)Streak camera on beam 10.

energy by bremsstrahlung emission, the minimum level that we could have observed is \(\sim 18\) J in suprathermal electrons or approximately 20 percent of the absorbed energy. If deposition occurs in the 0.5 \(\mu\)m plastic (whose initial thickness is \(\sim 30\) percent of the suprathermal electron range) then we are unable to detect if all of the absorbed energy is in the suprathermal electrons. This discussion does not include suprathermal electron losses to a fast ion expansion for which no measurements exist. It should be noted, however, that Argus and Shiva experiments at similar irradiation conditions (intensity and pulse width) but with thicker targets (thickness > 5 \(\mu\)m), suggests that \(< 5\) percent of the absorbed energy is deposited into the target by suprathermal electrons.

On the highest energy shot (81121712) small X-ray signals were obtained on the three lowest energy channels (6.1, 7.7, and 9 keV). The data quality, however, does not warrant the construction of a spectrum from these results which in addition may be compromised by the presence of X-rays from bound-bound transitions.

The two-dimensional time integrated spatial characteristics of the X-ray region were measured by an 8X magnification KB X-ray microscope viewing the rear side of the target with a line-of-sight along the incident laser axis. The 1000 \(\AA\) Al/3.2 \(\mu\)m mylar filter resulted in a channel response in the vicinity of \(\sim 0.8-1.2\) keV. A processed image (shot 81122207), recorded on Kodak No-Screen film, is shown in Fig. 6(a). This image provides a source "area" which is needed to determine the X-ray flashlamp brightness. Vertical and horizontal scans through the image center are displayed in Fig. 6(b) and (c). The overall dimension (full width 0.1 maximum) of the image is \(\sim 1000\) \(\mu\)m with a FWHM of \(\sim 750-820\) \(\mu\)m. The relatively soft edge of the image could be due to both time integration and the overlapping of the 10 beams. Whereas the overall image does not show any small scale length structure (time integration may again be responsible) there is a relatively long scale variation (1.5:1) in the X-ray image over a scale length of \(\sim 500-700\) \(\mu\)m.

It would be of considerable interest to relate the observed
B. X-Ray Spectra

The X-ray microscope image recorded in the target plane, but because of the focusing error (0.1 mm beam diameter) and large scale length (-0.5 mm beam diameter) employed in the experiment, it should be representative of an individual line-out of the near-field profile of one Shiva beam (beam #S) recorded during the experimental sequence. This was not realized to provide information on the time and space integrated X-ray spectrum emitted from both the front laser irradiated surface (see Fig. 4) as well as behind the flashlamp foil. Because they measure the spectrum which will be experienced by the X-ray laser medium the rear viewing measurements were of primary importance to these experiments. The procedure for calibrating the spectrographs and the film (Kodak SB-5) is written in an unpublished report [8]. Calibration is the single most uncertain quantity ($\pm 0.50$ percent in X-ray intensity) in determination of the absolute intensities for the X-ray lines emitted by the candidate flashlamp foils. The spectrographs were set up to measure the X-ray spectrum emitted in the X-1-1.2 keV (up to 1.4 keV for the front-viewing spectrographs) X-ray region. Both spectrographs used KAP (potassium acid phthalate) diffraction crystals for which 2d $\theta = 26.632 \text{ sr cm}^2$. The spectra were photon energy calibrated utilizing absorption edges from known material foils that were placed over the entrance aperture to the spectrographs. Calibration to known spectra features in the case of the Fe and Cr data was also utilized. Spectra were conservatively calibrated to within $\pm 5$ eV photon energy.

A 3000 Å period gold transmission grating coupled to a LLNL soft X-ray streak camera measured the time history (instrumental line resolution (FWHM) of $\tau_{\text{FWHM}}$ ~ 15-20 ps) of the L-band emission. The spectral resolution however, $(E/\Delta E \sim 10)$ is insufficient to observe individual lines. Examples of the data obtained with the transmission grating-streak camera are shown and summarized in Figs. 7 and 8. The time-integrated spectra with the same instrument from a Cr and Ni flashlamp, showing strong L-shell emission, are displayed in Fig. 7. The poor instrument resolution precludes observation of individual lines but it does show the expected result, namely that the energy centroid of the emission increases with target $Z$. In Fig. 8 as an example we show the time history of the L-shell emission from a Cr flashlamp. The rise time of the X-ray emission is consistent with a 100 ps driving laser pulse (the laser pulse is measured to Gaussian with a 106-120 ps FWHM) but it decays more slowly with a characteristic time of ~220 ps. The FWHM of the X-ray emission is ~200 ps which is 1.5-2 times greater than the laser pulse.

Typical time and space integrated spectra obtained from the Fe, Cr, and Ni flashlamp foils are shown in Figs. 9, 10, and 11, respectively. All of these data were obtained from a spectrograph at 35$^\circ$ to the target normal. In Fig. 12 we also show, for comparison, the important case of a Cr spectrum obtained with one of the rear-side spectrographs (38$^\circ$ to target normal). Except for the Ni spectrum, all data were energy calibrated using one of the known Li-like 3$\rightarrow$2 transitions. The specific calibration lines are shown on the figures. For the Ni spec-
Fig. 7. True integrated X-ray spectra produced by Ni and Cr flash-lamps and observed by a streaked-transmission grating spectrograph. ($\Delta E/E \sim 0.1$ FWHM).

Fig. 8. Time history of the X-ray emission from the peak intensity point of the L X-ray spectrum from a Cr flashlamp target. The time resolution of the streak camera is $\sim 20$ ps FWHM. The rise time and time duration are noted in the figure.

Fig. 9. $L \rightarrow M$ X-ray spectrum observed by a crystal spectrograph placed in front (laser interaction side) of Fe flashlamp foil.

trum, the spectral coverage cut off below the Li-like transition energy region and so we used one of the well-known Ne-like $3d \rightarrow 2p$ transitions (which is again noted on the figure).

The linewidths in the case of both instruments are dominated by source size. The width is $\sim 1.8$ eV FWHM for the front-side spectrograph, whereas it is $\sim 1.4$ eV FWHM for the rear-side spectrograph; the latter being smaller owing to a different instrument design and being located farther from the source.

The spectra are rich in line number and exhibit numerous transitions having large intensities. Looking at the Fe spec-

Fig. 10. Chromium $L \rightarrow M$ spectrum emitted by laser interactions side of foil.

Fig. 11. Ni $L \rightarrow M$ X-ray spectrum.

Fig. 12. (a) Chromium $L \rightarrow M$ spectrum emitted on backside of flashlamp. (b) Expanded version of chromium $L \rightarrow M$ spectrum emitted in transmission through flashlamp foil. Calibration lines and the location of the Be-like chromium $3d \rightarrow 2p$ possible laser pump transition are shown.
performed at LLNL early in the Novette experiment schedule.

the measure of the line's brightness at a given frequency which we can determine these line positions are currently in progress (from one rear-side spectrograph) illustrates the uncertainty in comparison to the kinetics calculations in the computer code.

mination of the flashlamp pump line brightness. To facilitate measurements which will improve the accuracy with which
ing from about 0.87 to 0.91 keV which should be associated

for an optically thick source in equilibrium; thus, if

Some of the more important spectra measured in our experiments were those from Cr since it was a prime candidate for pumping He-like fluorine to produce a 42.3 eV laser. The data obtained from Cr were also of higher quality than those obtained from the other candidate (Ni) so we will emphasize the Cr results. The Be-like chromium line necessary to pump the n = 4 level of He-like fluorine (899.78 eV) should occur at 899.58 eV. Examination of the spectrum shown in Fig. 12 (from one rear-side spectrograph) illustrates the uncertainty in spectral calibration. There is a distinct group of 5 lines occurring from about 0.87 to 0.91 keV which should be associated with Be-like 3d-2p transitions. Unfortunately, because of the uncertainty in our ±5 eV energy calibration, it is not possible to conclusively state that the desired overlap occurs. Further measurements which will improve the accuracy with which we can determine these line positions are currently in progress at KMS Fusion Industries (Ann Arbor, MI) and others will be performed at LLNL early in the Novette experiment schedule.

The primary objective of these measurements was the determination of the flashlamp pump line brightness. To facilitate comparison to the kinetics calculations in the computer code XRASER, we express the brightness in terms of modal photon density (photons/mode). The modal photon density is really the measure of the line's brightness at a given frequency which can be compared to that of a blackbody radiating at a prescribed temperature. $N_p = \exp(h\nu/kT) - 1)^{-1}$ photons/mode for an optically thick source in equilibrium; thus, if $h\nu = kT$, $N_p = 0.58$ photons/mode, and if $h\nu = 2.822$ $kT$ (peak of blackbody spectrum) $N_p = 0.063$ photons/mode, and etc. Stated alternatively, for a fixed photon energy, $N_p$ scales rapidly with $kT$, thus emphasizing the importance of heating the flashlamp to a relatively high electron temperature.

Flashlamp modal photon densities of approximately 0.01 photons/mode are necessary for most of the photoexcitation laser schemes [3].

Relating $N_p$ to parameters we actually measure gives the following relation:

$$N_p = \frac{[2.56 \times 10^{-24}] \cdot E_{hv}^3 \cdot \Delta \tau^{-1} \cdot A^{-1} \cdot I}{\Delta E_{\text{exp}} \cdot \Delta E_{\text{natural}}}$$

where $E_{hv}$ is the transition energy in eV, $\Delta \tau$ is the transition time duration (FWHM) in s, $A$ is the plasma emission area in cm$^2$, $\Delta E_{\text{exp}}/\Delta E_{\text{natural}}$ is the ratio of the experimental linewidth (FWHM) to the natural (and Doppler-broadened) linewidth, and $I$ is the measured intensity in units of keV cm$^{-2}$ sphere. For these experiments, $I$ (LLNL data) is uncertain to ±50 percent. The uncertainty in $\Delta \tau$ is not measured since the time duration of emission for individual lines was not determined and $\Delta E_{\text{exp}}/\Delta E_{\text{natural}}$ is known to ±50 percent leading to large uncertainty in $N_p$. Future experiments at KMS and LLNL will focus on reducing the error in each of these parameters. Table IV represents some modal photon intensities derived for the most intense lines in the Cr + CH and the Ni + CH spectra taken during these experiments. We have used the transmission-grating streak camera for $\Delta \tau$, the time duration laser-produced X-ray emission. In the Cr case, the lines assumed to be candidates for pumping the laser (i.e., from the Be-like sequence) are ~ one-half these values. The line brightness is somewhat smaller than the value presumed in calculating the photopumped X-ray laser schemes, namely 0.01 photons/mode. There is, however, considerable uncertainty in the data. Nonetheless, attempts to increase $N_p$ must be determined by experiments performed on Novette in the early phases of the X-ray laser experiments program. Methods to

We note, however, that striving for higher temperature can sometimes overstrip (ionize) the ions leading to less than optimum production efficiency for the parent ion of the pumping transition.
increase the value of $N_p$ by utilizing the wide range of irradiance conditions available at Novette (namely $L_L = 0.53 \mu m$ and higher intensities) are presently being considered and these options will be examined during an early measurement sequence at Novette.

IV. SUMMARY AND CONCLUSIONS

Table V summarizes all of the data obtained by both the front and rear spectrographs during these measurements. Points to note include: 1) these spectrographs agree on integral X-ray yield to within a factor of 2-3, except when target is normal to laser beam (this is no doubt a line-of-sight, i.e., opacity effect, or geometry problem). Using the Cr shots as an example, the total energy radiated in lines is $\sim 5$ percent (10 percent) of the incident (absorbed) laser energy; 2) spectrographs oriented at two different angles indicate anisotropy of emission particularly when the target is normal to laser (this gives our instruments an edge-on view and a somewhat greater than COS$^2$O correction is necessary to get agreement between the two LOS; we, therefore, can attribute the difference to bulk as well as individual line opacity effects; 3) differences in $I_{MAX}$ values

2Preliminary results from the Novette experiments are now available and it appears that $n_p \sim 0.01$ is achievable.
between front and rear are due to different resolving-power, intensity calibration, and perhaps source emissivity for front of foil versus back side.

In summary, we partially characterized the line radiation produced by potential flashlamp line sources. We have demonstrated the feasibility of the laser-heated flashlamp concept; namely, that a bright uniform source of $L \rightarrow M$ radiation can be produced. However, several areas of uncertainty have emerged as the result of performing these measurements: 1) we must improve the accuracy with which we determine flashlamp line centroid energy; 2) we must determine flashlamp line widths, and 3) we must measure the time duration of individual lines (i.e., with a high resolution spectrograph). As result of the experience gained in this early work, future measurements will provide much more accurate assessment of flashlamp line brightness. Methods to optimize (i.e., increase) flashlamp brightness must be explored since some X-ray laser schemes will be marginal at the present values. Experimental parameters which could effect the flashlamp output include laser wavelength, intensity, and flashlamp thickness.

ACKNOWLEDGMENT
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REFERENCES