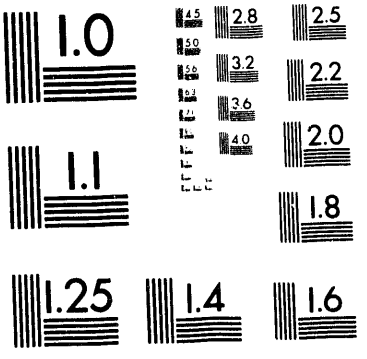
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

1 of 1

2

Conf-930722--29

UCRL- JC-112492
PREPRINT

Generation of Intense Ultrashort X-Ray Pulses (U)

D.C. Eder, R.A. London, M.D. Rosen, and G.L. Strobel[†]

Lawrence Livermore National Laboratory
Livermore, California

[†]University of Georgia
Macon, Georgia

This paper was prepared for publication in the
Proceedings of SPIE's International Symposium on
Optical Applied Science and Engineering,
Ultrashort Wavelength Lasers II
San Diego, CA July 11-16, 1993

August 1993

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.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California 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 products, 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 the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

RECEIVED
AUG 30 1993
OSTI

Generation of Intense Ultrashort X-Ray Pulses

D. C. Eder, R. A. London, M. D. Rosen, and G. L. Strobel

Lawrence Livermore National Laboratory, Livermore, CA 94550

ABSTRACT

Modeling of x-ray emission from targets heated by an ultrashort-pulse high-intensity optical laser is discussed. One application, using the emitted x rays, is pumping inner-shell photo-ionized x-ray lasers. Short wavelength lasing ($\lambda \leq 15$ Å) requires fast rise-time 1-3 keV x rays to ionize inner K-shell electrons. It has been shown that structured targets, consisting of grooves on a solid material or a composite of clusters, have high absorption. We model grooved targets as an ensemble of exploding foils finding that the rise time of x rays is rapid enough for pumping inner-shell x-ray lasers. We show that simple atomic models can overestimate the energy in x-ray emission bands. High-Z materials are found to have the highest conversion efficiency but mid-Z materials can be used to provide a band of emission at a particular energy. We show that the pondermotive inhibition of expansion has only a small effect on the x-ray emission. The emission of a Au plasma is found to be appropriate for pumping inner-shell lasing at 14.6 Å in Ne. The required optical laser intensity is of order 10^{17} W/cm^2 using a 100 fsec FWHM duration pulse. To produce a laser with a gain-length product of order 10 requires 5-15 J of optical energy.

1. INTRODUCTION

A number of laboratories now have ultrashort-pulse (≤100 fsec) optical lasers with energy approaching or of order 1 J.[1] An important use of these lasers is in the production of intense pulses of incoherent x rays. One problem in producing x rays from flat targets heated by ultrashort pulses is that the absorption and conversion efficiency decrease as the intensity increases.[2] This is the result of creating a very reflective plasma on the surface of the target.[3] This problem can be solved by using structured targets, consisting of grooves on a solid material or a composite of clusters (e.g., gold-black), that have high absorption.[2] There are a number of applications for an intense pulse of x rays that require different photon energies and different temporal properties. To obtain adequate time resolution of a rapid dynamical process, the pulse duration must be short. A target such as gold-black should give a short duration pulse because of the rapid expansion and cooling of the clusters after heating. For the application of pumping inner-shell x-ray lasers only the rise time of the x rays is important, not the total duration of emission. For this application, grooved targets can be used. They can be modeled more accurately than targets consisting of clusters have a wide range of sizes. We discuss the modeling of grooved targets as an ensemble of exploding foils. The time behavior of emission from solids and exploding foils has been studied previously.[4] In addition to studying the time behavior, we investigate the spectrum for high and mid-Z target materials. Modeling plays an important

role because the desired rise time of emission (≈200 fsec) is a factor of 10 faster than can be measured using present streak cameras.[5]

We provide some background on inner-shell x-ray lasing and the requirements on the ionizing x-ray pulse. We then discuss the modeling of grooved targets and the effect of different atomic models for a Au target material. We give results for two mid-Z materials, Cu and Se, and show the effect of including a pondermotive force. In the summary we comment on the prospects of inner-shell x-ray lasing.

2. REQUIREMENTS FOR INNER-SHELL X-RAY LASING

The prospect of lasing following inner-shell ionization is exciting because the wavelengths are significantly shorter (≤15 Å for K-shell ionization of Ne and higher Z elements) that what can be obtained with conventional collisional x-ray lasers.[6] However, the requirements on the x-ray source are quite severe. There are two aspects of the x-ray scheme that affect the x-ray requirements. First, the main depopulation process of the upper-laser level is not the desired radiative transition, but a rapid Auger decay. To establish a significant upper-level population, a very large x-ray flux is required. Second, the lower-level population build up in time because its decay processes are very small. This necessitates a very rapid rise of the x-ray pulse to achieve gain before the lower-level population destroys the inversion. Some of the relevant rates and transition energies for inner-shell lasing in Ne and Mg are given in Fig. 1. We use a hole notation where, for example, LL denotes a doubly ionized electronic structure with two holes in the L shell. This x-ray laser scheme has high quantum efficiency because the energy of the lasing transition (849 eV for Ne) is comparable to the energy needed to create the electron hole in the K shell (870 eV for Ne.

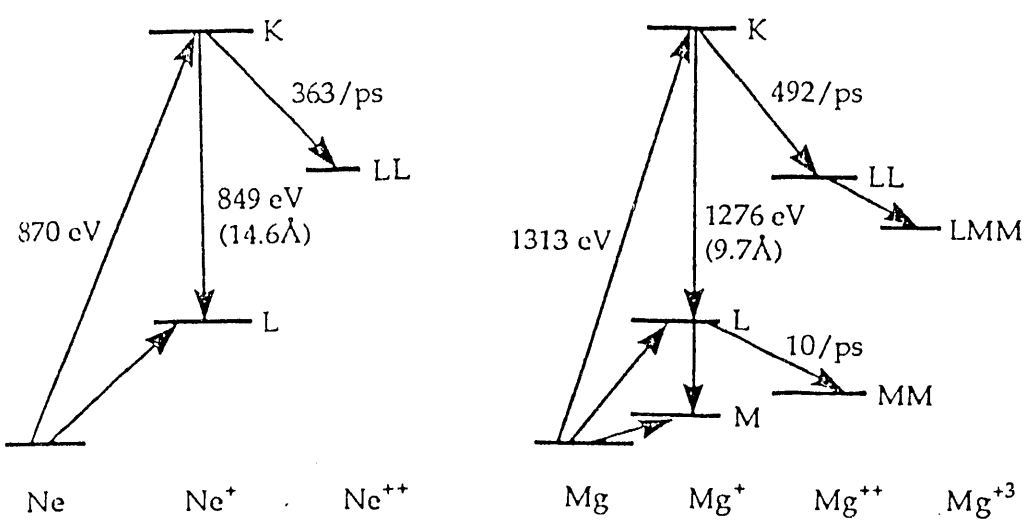

Figure 1. Relevant transitions for inner-shell photo-ionization of Neon and Magnesium. The Auger decay rates out of the upper and lower laser levels are given, as are the ionization and lasing transition energies.

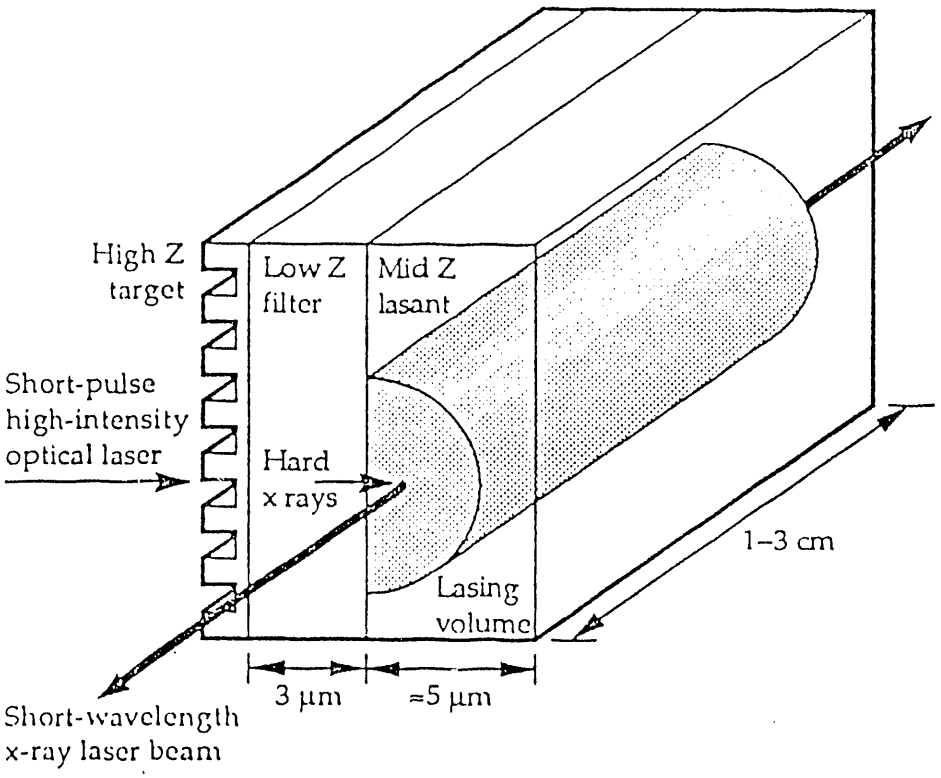

Figure 2. Schematic of a complete inner-shell photo-ionized x-ray laser.

A complete x-ray laser target for inner-shell lasing would consist of a thin x-ray source, a low energy filter, and a lasant material.[7,8] A schematic for such a target is shown in Fig. 2. In this geometry, the high-Z x-ray source must be thin enough to allow the x rays to pass through. We assume that it has grooves to improve absorption. The x rays must be filtered to reduce low energy photons that could ionize electrons out of the L shell but not the K shell, since ionization of L-shell electrons directly populates the lower-lasing level. To achieve a length of ionized material sufficient to have amplification of spontaneous emission or lasing, the driving laser is line focused onto the high-Z material. For gain coefficients of 5-15 per cm, lengths of 1-3 cm are desired.[7,8] Assuming a width of 5 μm, a 100 fsec pulse, and a laser intensity of order 10^{17} W/cm^2, one has energy requirements of 5-15 J. Lasers with these energies are not currently available but should become available in the near future given the rapid advances in recent years.

3. MODELING OF GROOVED TARGETS AS ENSEMBLE OF FOILS

It has been shown that the absorption for targets with grooved surfaces is high for driving laser conditions comparable to those being considered in this paper.[2] Targets consisting of a large number of small solid density clusters, with large voids giving an average density of approximately 0.3% solid, are also observed to have high absorption. We restrict our attention to grooved targets, in part, because the low density material is

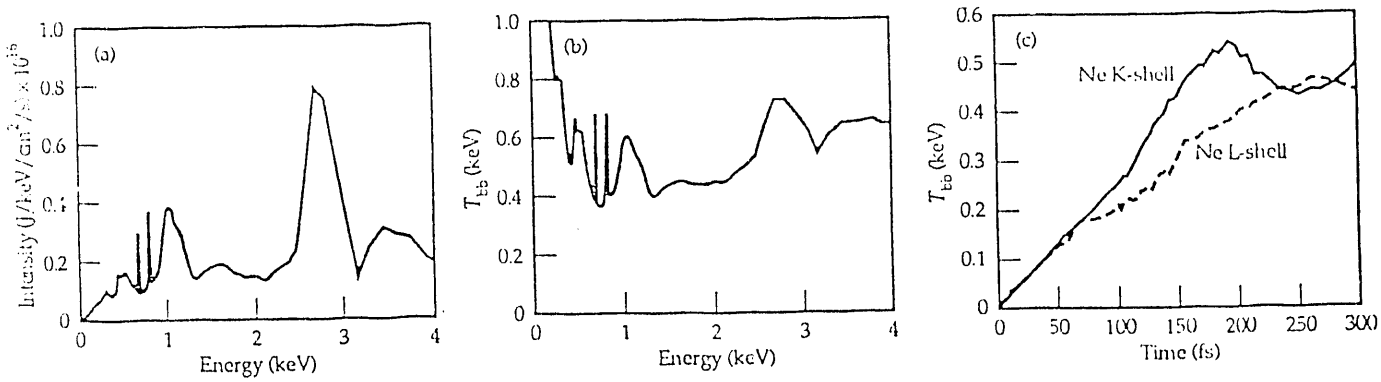

Figure 3. a) Spectrum of a 1000 Å Au target at a time 100 fsec after peak of 100 fsec (FWHM) pulse. The absorbed intensity on each side of the Au foil is 10^{17} W/cm^2. b) The spectrum expressed in terms of an equivalent black body temperature. c) Time dependent equivalent black body temperature used for K- and L-shell ionization. The peak of the heating pulse is at 150 fsec.

more difficult to model given the large range of cluster sizes present. For grooved targets, high absorption requires groove depths of order 2000 Å with a periodicity equal to approximately one half the wavelength of the incident light. We consider a target with grooves that are 2000 Å wide with a period of 3000 Å. We model this target as an ensemble of 1000 Å wide planar expanding exploding foils. The spacing between the foils (2000 Å) is assumed large enough that the expansion of one foil does not affect the expansion of neighboring foils for the times of interest. Our calculations show that this is a reasonable assumption. We do not address the issue of coupling of the incident laser light to the foil, but just assume that it is absorbed in a skin depth. The conduction, hydrodynamics, atomic kinetics, and the resulting emitted x-ray spectrum are calculated with the LASNEX code.[9]

High-Z materials have bands of emissions associated with the large number of transitions between given pairs of principal quantum levels. In addition, many different ionization stages are present which also contribute to the width of the bands. For example, in Au, the bands associated with n = 5 to n = 4 emission is at approximately 1 keV and the n = 4 to n = 3 emission is around 2.7 keV. The width and the peak of the emission depend on the incident laser intensity through the ionization balance and temperature. Figure 3a gives the calculated spectrum for a 1000 Å thick Au target with an absorbed intensity of 10^{17} W/cm^2 on each side. The spectrum is shown for a time 100 fsec after the peak of the 100 fsec FWHM pulse. We also show the spectrum in terms of the equivalent black body temperature T_{bb} in Fig. 3b. The emission from the Au target is appropriate for inner-shell ionization of Ne. In Fig. 3c we show the time dependence of the radiation just above the K edge of Ne and the time dependence of the radiation above the L edge. The harder x-rays are observed to have a faster rise with the turn over at 200 fsec the result of the emission band moving to higher energy.

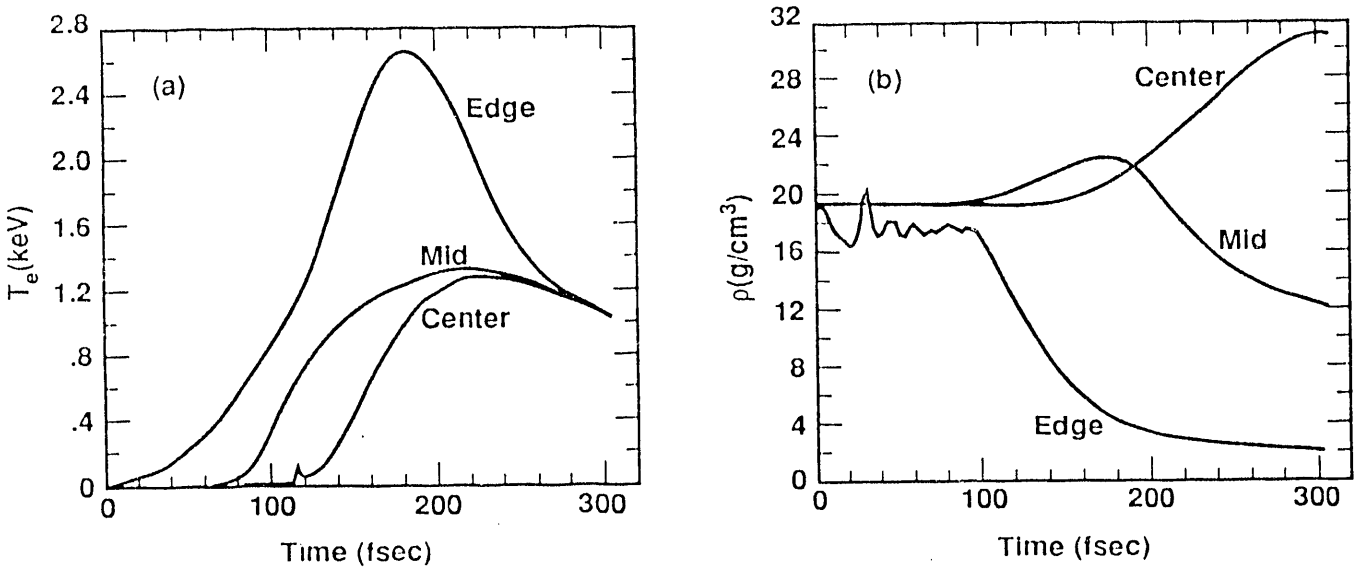

Figure 4. a) The time dependent temperature for edge, center, and the region midway between the edge and center of foil that produced spectra shown in Fig. 3. b) The time dependent density for the three regions.

The outside edges of the 1000 Å foil are calculated to reach temperatures greater than 2 keV and drop to densities approximately 10% of solid density. The temperature at the center of the foil increases to 1.2 keV and the center is compressed to a density about 50% greater than solid density. Figure 4 gives the time dependent temperature and density for edge, center, and the region midway between the edge and center. The conditions plotted for the edge region corresponds to a zone in the calculation that is initially 50 Å from the outside of the 1000 Å foil. The average density of the foil at the end of the pulse is approximately 2/3 of solid density.

4. EFFECT OF ATOMIC MODELS ON CALCULATED X-RAY SPECTRUM

The calculated Au spectrum shown in Fig. 3 used an atomic kinetic model based on the average-atom approximation. In this approximation, one does not treat individual ionization stages, but works with an averaged ion with a fractional population of electrons in each bound level. However, within this approximation there is a freedom in how many quantum levels are included. Some of our earlier calculations[7] used an average-atom model[10] based on a screened hydrogenic potential, but it ignores angular momentum and spin. In this model, where only principal quantum numbers are included, the width of each energy level is determined by accounting for overlapping lines due to the different configurations of ions. Our current calculations use a more detailed average-atom model which includes the effect of spin-orbit coupling and the effect that orbitals with different angular momentum penetrate different distances inside the screening electrons. For comparison, Fig. 5 shows the calculated spectrum using the simpler hydrogenic average-atom model for the same conditions as used in Fig. 3. The use of the less detailed model results in the two major emission bands being narrower with higher peak values. In

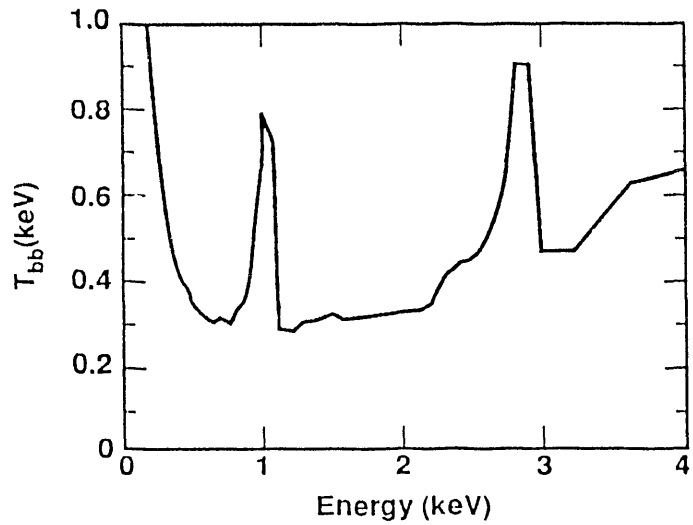

Figure 5. The calculated spectrum for Au foil using the hydrogenic average-atom model to be compared with Fig. 3b.

addition, structure in the spectrum seen with the more detailed model, Fig. 3b, is not present using the hydrogenic model.

The difference between the two average-atom atomic kinetic models provides motivation to study even more detailed models that do not use the average-atom approximation. However, for high-Z materials, the requirements for such models and the computational costs to use them are very high. Detailed atomic models with hundreds of levels have been constructed for a few ionization stages around Ni-like W.[11] These model are used to calculated x-ray lasing in Ni-like W and Ta.[12] In order to calculate the time dependent x-ray emission from a high-Z target heated by short pulse laser, atomic models covering a wide range of ionization stages are required. The construction of a detailed atomic model for a wide range of ionization stages is difficult. In addition, the computational cost for a complete time-dependent calculation using atomic models with thousands of levels, where a very large number of lines contribute to the spectrum, is very high. We propose that a relatively inexpensive way to compare the average-atom approximation to a more detailed model is to pick an element and an electron density and temperature where the plasma is primarily in ionization stages where atomic models already exist. For these conditions, one can calculated steady-state emission with the two models to see if the average-atom model is in reasonable agreement with a detailed model that includes individual ionization stages.

5. MID-Z TARGETS AND THE EFFECTS OF PONDERMOTIVE FORCE

The emission bands of Au and other high-Z materials can be shifted to higher or lower energies to a limited extent by varying the intensity and thus the ionization stage of the heated ions. However, to obtain a band of emission at a particular energy, mid-Z target

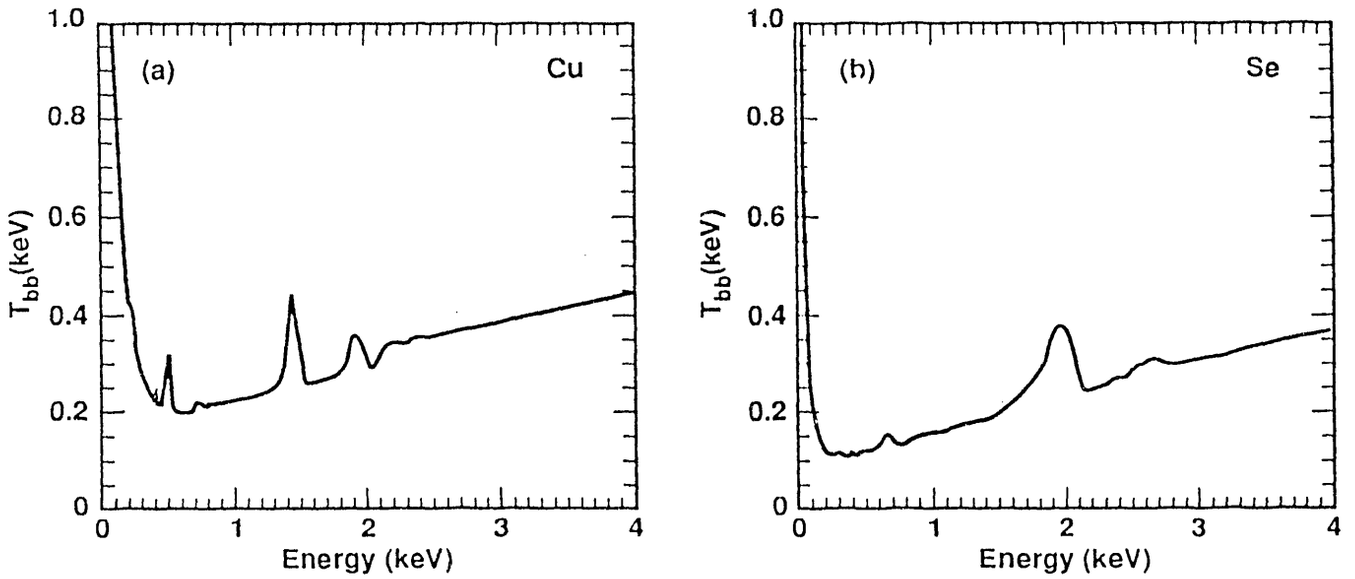

Figure 6. a) The calculated spectrum for a 1000 Å wide foil of Cu heated from both sides by a 100 fsec pulse with an absorbed intensity of 10^{17} W/cm^2. b) The same as for a) but using a Se foil.

material can be useful. For example, inner-shell lasing in Mg and Si requires x rays with photon energies above 1.3 and 1.8 keV, respectively. In Fig. 6 we show the calculated spectrum for a 1000 Å wide foils of Cu and Se heated from both sides by a 100 fsec pulse with an absorbed intensity of 10^{17} W/cm^2. The calculated emission peaks for Cu and Se overlay the maxima of the K-shell photo-ionization cross sections of Mg and Si, respectively.

For a 1000 Å Au foil heated with the same pulse discussed above (spectrum shown in Fig. 3), approximately 10% of the incident energy is radiated by the end of the pulse. For Cu and Se, the corresponding amounts are 1.5 and 0.7%. This is explained, in part, by the lower densities of Cu and Se compared to Au. The ratio of heated mass in Au, Cu, and Se is 4:2:1, respectively. The remaining factor of approximately 3 shows the higher conversion efficiency of high-Z materials. The optimum target material to pump a given inner-shell x-ray lasers depends on details of the low energy filter and on the energy dependance of the K-shell photo-ionization cross section.

The expansion of the Au foil during the pulse is relatively small. However, for Cu and Se there is a larger decrease in the density during the pulse. It has been observed that the pondermotive force of the laser can inhibit the expansion of planar targets[13] and one would expect that similar effects inside a grooved target. The calculation of the pondermotive force is outside the context of the simple model we use for absorption. However, we can add an arbitrary pondermotive pressure in the hydrodynamic calculations and determine the effect on the calculated emission. In Fig. 7a we show the

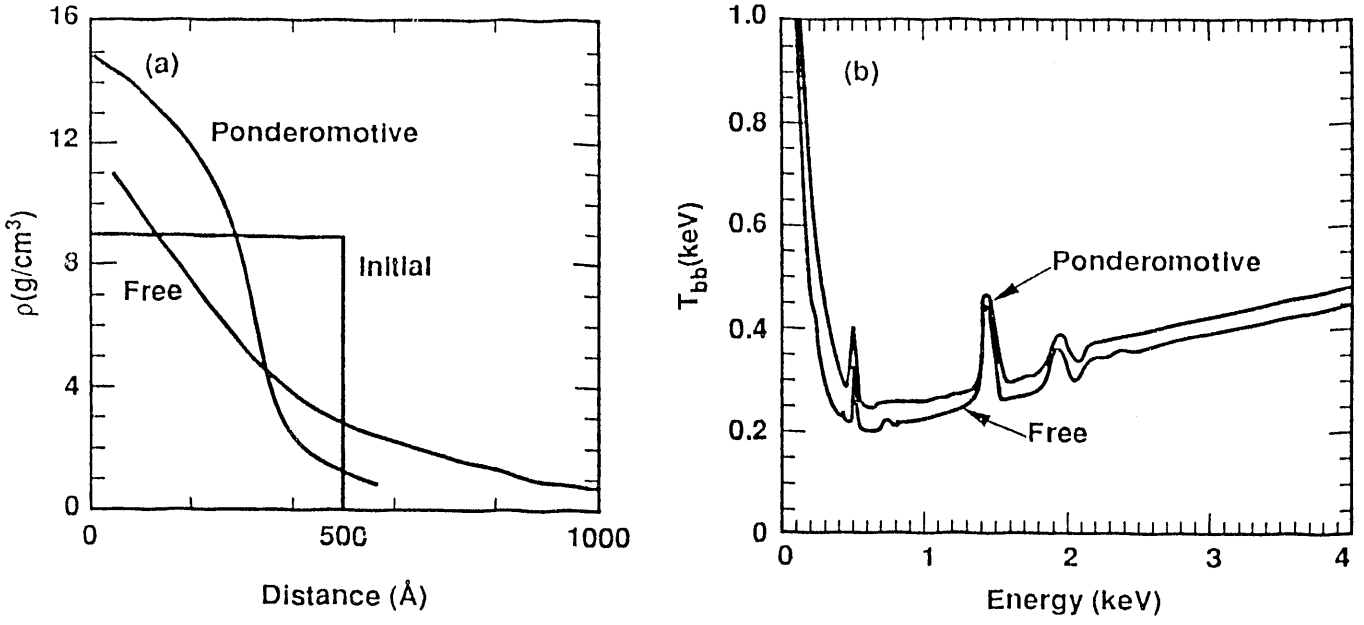

Figure 7. a) The initial Cu density profile, profile with free expansion, and profile affected by a specified pondermotive pressure. b) The calculated emission spectrum for the two cases.

density profile at the end of the heating pulse for a Cu target with free expansion, and for one where the expansion is significantly affected by the pondermotive pressure. The initial profile is shown for comparison. The effect on the calculated emission for these two cases is relatively small as shown in Fig. 7b.

6. SUMMARY AND PROSPECTS FOR INNER-SHELL X-RAY LASING

Calculations of the emission from both high and mid-Z grooved targets heated by an ultrashort-pulse high-intensity laser show that an intense pulse of x rays with a rapid rise time can be produced. The decrease of emission after the pulse is not as rapid, with the higher density foil (Au) emitting for the longest time. For the application considered in this paper, pumping inner-shell x-ray lasers, only the rapid rise of emission is important. For applications that require a short duration of hard x-ray emission, it is expected that structured targets, e.g., gold-black, consisting of a large number of small solid density clusters would be more appropriate because of the rapid expansion of the clusters results in faster cooling. We have shown the importance of using an atomic model that included the effect of angular momentum in calculating the emission from a Au target. The use of mid-Z materials results in lower overall conversion to x rays, but a band of emission can be obtained at a desired energy. We find that including a pondermotive pressure to inhibit the expansion of a Cu target has only a small effect on the x-ray emission. In general, the calculated intensities of x rays from grooved targets ($T_{bb} \approx 4$ keV) is sufficient to achieve significant population inversion and gain following inner-shell ionization. The requirement of using a line focus to heat an area of the target that is of order 5 μm wide by 1 to 3 cm long results in an absorbed energy of 5 to 15 J for the assumed intensity of

10^{17} W/cm^2 and a 100 fsec pulse. These energies are approximately a factor of 10 higher than what is currently available but such lasers should be available in the near future. If high gain coefficients (> 10 cm^{-1}) could be obtained, shorter lengths can be used with a corresponding reduction in the energy requirement for the driving laser. Given the rapid advances of ultrashort pulse optical lasers, the prospect for inner-shell x-ray lasing is quite high.

7. ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

8. REFERENCES

[1] SPIE Proceedings on Short-Pulse High-Intensity Lasers and Applications II Vol. 1860, Los Angeles, January 1993.

[2] M. M. Murname, H. C. Kapteyn, S. P. Gordon, J. Bokor, E. N. Glytsis, and R. W. Falcone, Appl. Phys. Lett. **62**, 1068 (1993).

[3] H. M. Milchberg, R. R. Freeman, S. C. Davey, and R. M. More, Phys. Rev. Lett. **61**, 2364 (1988).

[4] M. D. Rosen, SPIE Proceedings Vol. 1229, 160 (Femtosecond to Nanosecond High-Intensity Lasers and Applications, LA 1990).

[5] M. M. Murname, H. C. Kapteyn, and R. W. Falcone, Appl. Phys. Lett. **56**, 1948 (1990).

[6] *X-Ray Lasers* 1992, Proceedings of the 3rd International Colloquium on X-Ray Lasers, IOP Conf Ser. 125, edited by E. E. Fill (IOP, Bristol, England, 1992).

[7] G. L. Strobel, D. C. Eder, R. A. London, M. D. Rosen, R. W. Falcone, and S. P Gordon, "Inner-shell photo-ionized x-ray laser schemes," in SPIE Proceedings Vol. 1860: Short-Pulse High-Intensity Lasers and Applications, ed. H. A. Baldis (SPIE, Bellingham, Washington 1993)

[8] H. C. Kapteyn, Applied Optics **31**, 4931-4939 (1992).

[9] G. B. Zimmerman and W. L. Kruer, Comm. Plasma Phys. Controlled Fusion **11**, 51 (19).

[10] W. A. Lokke and W. H. Grasberger, Lawrence Livermore National Laboratory UCRL-52276 (Available from: National Technical Information Servide, U. S. Dept. of Commerce, 5285 Port Royal Road, Springfield, VA 22161) (1977).

[11] A. L. Osterheld, B. K. F. Young, R. S. Walling, W. H. Goldstein, J. H. Scofield, M. Chen, G. Shimkaveg, M. Carter, R. Shepherd, B. J. MacGowan, L. B. DaSilva, D. Matthews, S. Maxon, R. A. London, and R. E. Stewart, *X-Ray Lasers* 1992, Proceedings of the 3rd International Colloquium on X-Ray Lasers, IOP Conf Ser. 125, edited by E. E. Fill (IOP, Bristol, England), 309 (1992)

[12] S. Maxon, K. G. Estabrook, M. K. Prasad, A. L. Osterheld, R. A. London, and D. C. Eder, Phys. Rev. Lett. **70**, 2285 (1993).

[13] G. Mourou and D. Umstadter, Phys. Fluids B 4, 2315 (1992).

DATE
FILMED
10/25/93

END