The x-ray laser: a new era in laser technology

Have advances in fact been made? Yes, report Charles B. Stevens and a number of Lawrence Livermore scientists.

The x-ray laser promises a revolution in medicine and biology as well as in defense, opening up a new world of lasing on the subatomic scale. Imagine the leap in understanding of the process of life that will come from being able to watch "movies" of cell life on a subatomic scale. No field of scientific research will be excluded from this technological advance—from microbiology to controlled thermonuclear fusion research. The coming into operation of Lawrence Livermore National Laboratory's powerful 10-beam Nova laser will greatly enhance the development of x-ray laser technology, and we can expect continuing breakthroughs.

For the x-ray laser as a defensive weapon, there are also breakthroughs on the horizon. Lawrence Livermore has developed larger-scale x-ray lasers, powered by nuclear explosives, as an effective defensive weapon against nuclear-tipped missiles. In fact, according to many experts, the nuclear-pumped x-ray laser offers the most potent means of making ballistic missiles "impotent and obsolete." More advanced designs, currently being studied, are reported to have sufficient firepower such that one x-ray laser module, lofted on one defense missile interceptor, could have the capability of destroying entire fleets of Soviet ICBMs.

The vehemence of the attacks on Lawrence Livermore and its x-ray laser development seem to be in direct proportion to the promise of the technology. The Soviets directly and indirectly through their allies in the U.S. anti-beam-defense lobby have showered the laboratory with slanders, even to the point that critics claim no advances have occurred with the program, that the x-ray laser advocates are making it all up to make themselves look good, and that flawed instrumentation was responsible for alleged advances. The *Los Angeles Times*, the *New York Times*, and *Science* magazine figured prominently in this disinformation campaign against the lab during late 1985.

Ironically, as the following material by the Livermore staff demonstrates, much of the important scientific basis for x-ray lasing was developed by Soviet scientists. It is also the case, despite propaganda claiming that the poor Soviets are trailing behind the United States in this area, that the Soviet R&D effort in x-ray lasing is at least 10 times that of the United States.

What follows are excerpts from a series of articles by Lawrence Livermore National Laboratory scientists in the lab's *Energy and Technology Review* June and November 1985 issues (UCRL-52000-85-6 and UCRL-52000-85-11), reviewing the history, technology, and potential of the x-ray laser. The authors include Mordecai D. Rosen, Peter L. Hagelstein, Dennis L. Matthews, Kenneth R. Manes, Glenn D. Kamback, Mark J. Eckart, and Natale M. Ceglio.

1) X-ray lasing

For over a decade, workers within the laser community have sought to produce coherent radiation at extreme-ultraviolet or soft-x-ray wavelengths. Although there is no general agreement on precisely what regions of the spectrum these terms designate, we may regard the extreme-ultraviolet regime as including wavelengths somewhat less than 10 nanometers (nm) and the soft-x-ray regime as those wavelengths between 10 and 2 nm; the respective energies range from 10 to 124 electron volts (eV) and from 124 to 620 eV.

Although a variety of theoretical schemes has been proposed and a number of laboratory experiments carried out, none, until recently, has resulted in confirmed x-ray lasing. In October 1984, a team of Lawrence Livermore scientists announced a well-diagnosed series of experiments that unambiguously demonstrated coherent amplification at wavelengths characteristic of the extreme-ultraviolet region. In addition to encouraging other experimental efforts, their success has generated considerable interest in applications of this fledgling technology.

All stimulated emission of coherent radiation depends on producing a population inversion in the lasant medium [see box]. In principle, the only distinctive feature of lasing at wavelengths shorter than the visible is the higher energy of the lasing transitions required. In practice, however, such transitions have proved extremely difficult to invert.

The appoach that was successfully utilized in the LLNL experiments was that of electron collisional excitation. To generate a plasma, we irradiate a thin-film target with optical wavelength laser light. Free electrons in the plasma collide with ions, exciting *2p* electrons, either directly or otherwise, to the *3p* state. This is followed by very fast radiative decay out of the *3s* state, creating a population inversion between the *3s* and *3p* states. Stimulated emission is then initiated by (slower) spontaneous decay from a *3p* to a *3s* state [**Figure 1**]. Although other collisional excitation schemes have been proposed, the *3p-3s* approach more or less dominates the field, and now seems to be synonymous with this scheme.

An electron collisional excitation scheme for short-wavelength lasing was first published in 1972 as an extension of optical *3p-3s* neon II lasers into the extreme-ultraviolet or soft-x-ray regimes. The first quantitive analysis of kinetics and gain in *3p-3s* transitions was published in 1974.

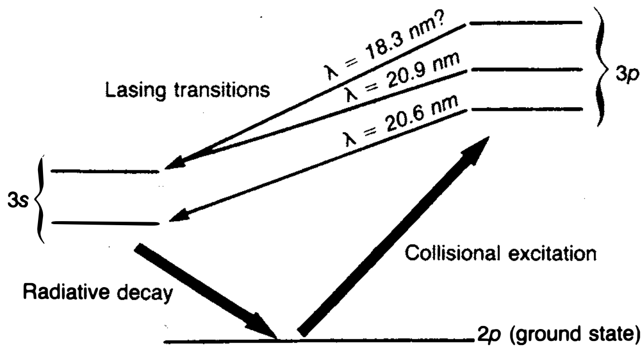
The earliest positive experimental results were published in the Soviet Union in 1977, reporting 10 nanojoules (nJ) of laser light near 60 nm on the diagnostic film and an inferred total output of one microjoule from *3p-3s* transitions in calcium. The investigators pumped a calcium plasma produced by irradiating a target with pulses from a neodymium laser having pulse lengths from 2.5 to 5 ns and a pulse energy of 30 J.

We have found no reports of the Soviet experiment being replicated elsewhere. Unfortunately, no precise wavelengths were reported; otherwise, it might have been possible to determine whether the lasing lines resulted from monopole excitation [that is, excitation by collision with free electrons in the plasma], as one would expect from theory, or by other mechanisms. Consequently, controversy continues as to whether lasing at short wavelengths was actually demonstrated.

2) X-ray lasing research at LLNL

Our work has focused almost entirely on excitation and decay sequences in neon-like ions—that is, ions stripped of all but 10 electrons. (Carbon-like and nickel-like ions are also candidates for short-wavelength lasing, but it is much easier to produce a plasma consisting of about half neon-like ions than one of half carbon-like or half nickel-like ions.)

Figure 1
Lasing transitions

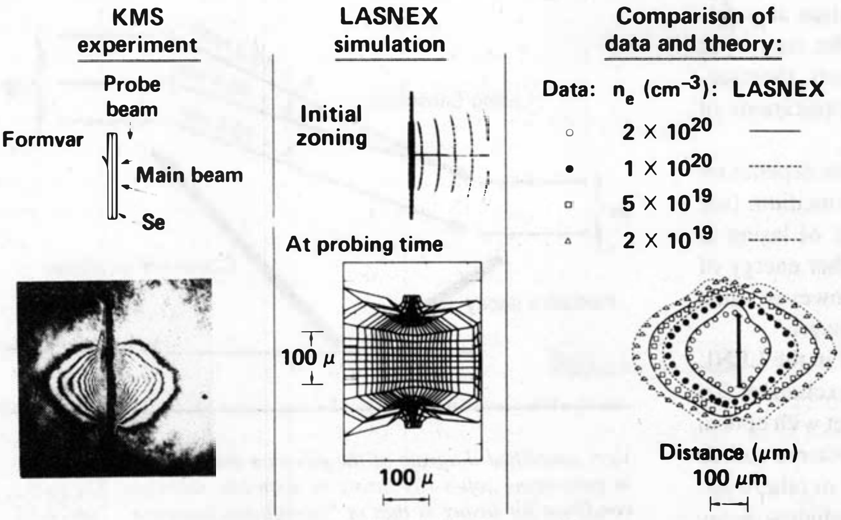


Very simplified diagram of the electron atomic orbitals utilized in generating soft-x-ray lasing in neon-like selenium. The precondition for lasing is that of "population-inversion," which occurs when atomic electrons are driven—excited—from a ground state orbit to a high energy orbit. Simultaneously there must exist intermediate orbits, between this high energy orbit and the ground state orbit, which are unpopulated—that is, no electrons occupy them. In this schema, the 2p *is the ground state orbit; three 3*p *orbits provide the excited, high energy orbits; and the two 3s provide the unpopulated intermediate orbits required for lasing. When a plasma made up of neon-like selenium ions and free electrons is brought to the requisite temperature and density through irradiation with optical laser light, the free electrons will "collisionally excite" electrons the high energy 3*p *orbitals. Electromagnetic radiation emitted from the excited ions will ensure that the intermediate 3s orbitals are unpopulated (radiative decay). Therefore, as shown, there exist three different, possible soft-x-ray lasing transitions at wavelengths of 18.3 nm, 20.9 nm, and 20.6 nm.*

The x-ray laser targets used in the LLNL experiments consist of thin foils of selenium and yttrium. Theory suggests selenium as a preferred lasing medium. Given the available power and wavelength of Novette [the predecessor to the Nova laser] as the driving laser, elements with lower atomic number (Z) tend to overionize, and those of higher Z have inadequate *2p-3p* collisional excitation rates.

When irradiated by light from the Laboratory's Novette laser, the x-ray laser target explodes to generate a roughly cylindrical plasma that contains neon-like ions. The experiment is carefully designed to produce a uniform electron density in the plasma; this allows the stimulated soft-x-ray emission to proceed straight down the long axis of the plasma cylinder with minimal refraction in the radial direction, thereby maintaining gain.

Figure 2
Predicted evolution of the density profile of the exploding foil as confirmed by interferometry



The KMS experiment (left, top) shows a diagram of the selenium foil, which was deposited onto a layer of Formvar. The lower part is an actual holographic interferogram of the plasma that results from one-sided irradiation of the foil by the main beam of an optical laser. The interferogram provides a means for determining the plasma density. At center is the LASNEX computer simulation of expected plasma densities following optical laser irradiation. At right is a comparison of computer simulation theoretical projections and KMS experimental data.

Our design goal is to produce a plasma with:

- a flat electron density of approximately 5×10^{20} cm^{-3}
- a flat temperature profile
- a scale length of a least 100 μm

These conditions must last at least 100 ps, which, according to theory, will produce an appreciable density of neon-like ions and therefore a significant gain. These values are motivated by simple considerations. For a system with an electron density gradient of 5×10^{20} cm^{-3} and a scale length of 100 μm, a 50 eV x-ray will refract about 100 μm as it proceeds 1 cm down the gain medium, thereby just staying within the high gain region. The transit time for the x-rays down the 1 cm is about 33 ps, which yields the requirement of a plasma duration of 100 ps or so.

Lasnex and Xraser

In designing our x-ray laser experiments, we make extensive use of two computer codes, *Lasnex* and *Xraser*. *Lasnex* is a two-dimensional hydrodynamics code that simulates interactions between the laser light and the targets (in our case, thin foils). As we understand the processes at work, the target absorbs the laser energy primarily via the classical process of inverse bremsstrahlung. The free electrons oscillate in a reversible manner in the laser's electric field. Upon colliding with an ion, the electron's oscillatory energy is converted irreversibly into random thermal energy. In this way, the plasma absorbs the laser energy.

The laser energy is absorbed only at electron densities equal to or less than the critical density, which for the Novette green light is 4×10^{21} cm^{-3}. Thermal conduction then transports the heat into the denser parts of the target. For the thin foils that we have designed, the thermal-conduction wave burns through the entire target before the termination of the laser pulse itself. The target thus becomes relatively dense and hot. It relieves this high pressure by exploding and expanding rapidly. The *Lasnex* computer code models this entire sequence of physical processes. Since it was introduced in the 1970s, *Lasnex* has been repeatedly extended, refined, and tested. In particular, it has been used with great success in modeling high-*Z*, laser-generated plasmas. Thus, we have developed considerable confidence in its predictions.

The second code, *Xraser*, was developed by P. Hagelstein. It uses the hydrodynamics input from *Lasnex*, together with atomic-physics data, to calculate electronic energy-level populations, resonant line transfer, and amplification. More specifically, *Xraser* accepts from *Lasnex* such quantities as the time-evolving temperatures of electrons and ions, densities, and flow fields. These data are then combined with previously calculated electron-level energies, radiative rates, and collision rates to yield predictions of gain and of the fraction of the plasma medium in various ionization states. Once the theoretical predictions for density, temperature, and ionization state are fully confirmed by experiment, we will be able to predict gain with greater confidence.

To facilitate direct comparison of the *Xraser* results with experimental data, a postprocessing code, *Spectre*, is used to predict the brightness of an emission line in any particular line of sight (including the effects of one-dimensional refraction).

To test the *Lasnex* and *Xraser* modeling of the exploding-foil, x-ray laser targets, preliminary experiments were performed at KMS Fusion, Inc., Ann Arbor, Michigan, in 1984. In these experiments, a single beam of 0.53-μm laser light was used to illuminate selenium thin-foil targets [**Figure 2**].

Our successful demonstration of lasing at soft-x-ray wavelengths was made possible, in large part, by the accuracy of our theoretical modeling with *Lasnex* and *Xraser* and by our theoretical understanding of the processes at work in short-wavelength lasing. However, there are areas of this subject that we still do not understand properly, as revealed, for example, by the weakness of the $J = 0$ to $J = 1$ lasing line.

It should be noted that our successful x-ray lasing experiments were single-pass—that is, the stimulated emission was not further amplified by multiple reflection in a cavity oscillator, as is standard practice in optical lasers. Short wavelength lasers will require new technology to achieve resonant amplification.

Most x-ray laser experiments are being conducted, with new laser technologies applied as they become available. The data obtained will be incorporated into our modeling codes, enabling us to refine and extend our theoretical understanding of short-wavelength lasing.

3) The diagnostics

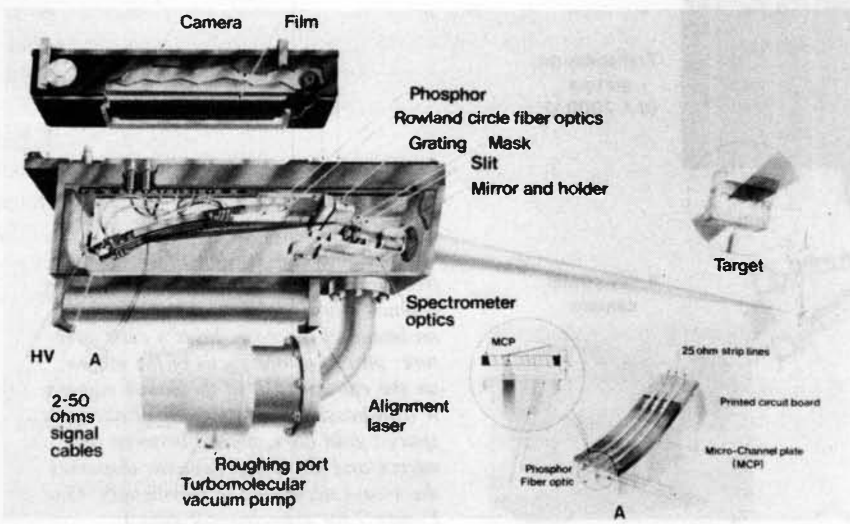
To collect evidence that the radiation detected in our x-ray laser experiments was indeed produced by lasing, we developed unique diagnostic capabilities to provide temporally, spatially, and directionally resolved soft-x-ray spectra. These innovations made our x-ray laser experiments some of the most thoroughly diagnosed experiments ever attempted.

Whenever the beam from one of our high-powered lasers strikes a target of any kind, a wide variety of radiation is produced. There is, of course, scattered laser light. There also is a broad spectrum of blackbody radiation from incandescent gases, as well as line radiation from resonant processes. The task of the diagnostic instruments in our x-ray laser experiments was to distinguish and characterize those x-rays produced by laser activity amidst all the other background radiation.

Ordinary laser light is directional, coherent, highly monochromatic, and, in many cases, pulsed. One can use an interferometer to demonstrate the coherence of ordinary laser light, but there is no similar instrument that works with soft-x-rays. The usual instrument for measuring the wavelength of light and for demonstrating the monochromaticity of an ordinary laser is a spectrometer. However, conventional x-ray spectrometers lack the sensitivity and discrimination to detect the radiation from our x-ray laser experiments. Therefore, to detect a directional beam of highly monochromatic x-rays of the appropriate energy occurring at the right time in the Novette laser pulse, we had to design our own high-sensitivity, time-resolving x-ray spectrometers. There are many ways to demonstrate the directionality of an ordinary laser beam, especially when it can be operated in a dark room. In our x-ray laser experiments, the flood of stray radiation (inherent in all laser irradiation experiments) eliminated most of these easy ways. Instead, we had to use duplicate spectrometers, one in the beam (on axis) and one at an angle of 77° out of it (off axis), and observe the difference in their readings.

Figure 3

MCPIGS Micro-channel plate intensified grazing incidence spectrometer



This Microchannel-Plate Intensified Grazing-Incidence Spectrometer (MCPIGS) provides time-resolved measurement of the spectra of plasma radiation during x-ray laser experiments. Plasma radiation coming through the entrance slit strikes the spherical reflection grating at a small angle (grazing incidence). It is then dispersed according to wavelength and focused into lines on a curved microchannel plate, which transforms incident x-rays into avalanches of electrons. Separate conductive strips define different regions of the microchannel plate that can be each turned on or off at will. Thus, this provides three separate images of the radiation spectrum at different times. (See Figure 6 for experimental data.)

Finally, we knew that the conditions suitable for x-ray laser action would occur for only a very short time during the Novette laser pulse. It takes time (fractions of a nanosecond) to deposit enough energy to vaporize the target foil and heat the vapors to a plasma. Shortly thereafter (in a few nanoseconds at most), the plasma dissipates and cools. Only when the plasma is both hot and dense, in the time between buildup and dissipation, can it act like a laser.

The shortness of the x-ray laser pulse was, actually, an advantage in our experiments. Computer modeling of the interaction of the Novette beams with the target indicated exactly when to expect this pulse. Thus, we could ignore background light that reached the detectors either too early or too late, greatly improving the signal-to-background ratio. To take advantage of this feature, we designed our instruments to provide time-resolved data.

Furthermore, because laser light is stimulated emission, the beam intensity varies nearly exponentially with the length of the laser cavity when all other parameters are held constant.

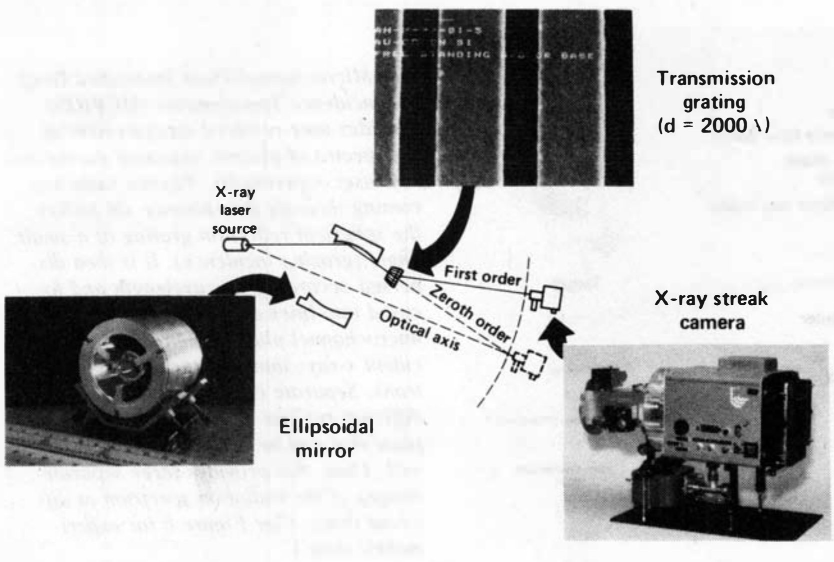
To demonstrate this feature, our spectrometers had to be able to measure the absolute intensity of the emitted x-rays over a series of experiments in which we varied the length of the selenium or yttrium foil (and thereby the length of the laser cavity) exposed to the Novette laser light.

Microchannel-Plate Grazing-Incidence Spectrometer. Although x-rays cannot be reflected back toward their source with surface mirrors, they can be reflected at a small angle when they strike a mirror at grazing incidence. This is the basis for our microchannel-plate grazing-incidence spectrometer [MCPIGS], in which x-rays are dispersed according to wavelength by a concave grating set almost edge on to the beam (**Figure 3**).

With a pair of these spectrometers, one on the x-ray-laser target axis and one 77° off that axis to provide a measurement of directionality, we were able to detect target radiation between 12.5 and 27 nm with 250-ps temporal resolution, high spectral resolution ($\lambda/\Delta\lambda = 1{,}800$), and a line-radiation detection threshold of 6×10^{-7} *J/sr*. This spectral bandwidth enabled us to detect radiation from $n = 3$ to $n = 3$ transitions of selenium ions in or near the neon-like state. The intensity of the x-ray lasing lines increases as the foil length is increased.

Transmission-Grating Streak Spectrometer. Another way to disperse x-rays into a spectrum is with a transmission grating. This makes it possible to use an ellipsoidal mirror that focuses an achromatic [wavelength-independent] image of the radiation source onto the focal plane [**Figure 4**]. The transmission grating disperses this image into its constituent chromatic components or wavelengths. To obtain time resolution, we added an x-ray streak camera to streak the spectrally dispersed images in time. The resulting instrument, known as the transmission-grating streak spectrometer (TGSS), provides a two-dimensional data record of the spatially and temporally resolved spectrum from the x-ray laser target. The TGSS produces an image of the x-ray laser output (with an ellipsoidal mirror) that is separated horizontally into its constituent wavelengths (with a transmission grating) and resolved vertically in time (with a streak camera). At any given wavelength, then, a time-resolved image of the source is provided. This is accomplished with high sensitivity as a result of the large collection solid angle of the ellipsoidal

Figure 4
Transmission grating streaked spectrograph: TGSS-EM



The transmission-grating streak spectrometer (TGSS), showing the grazing-incidence ellipsoidal mirror, which forms an image of the x-ray laser's exist aperture, placed at one focus of the ellipse, on the entrance slit of the streak camera. A transmission grating made of narrowly spaced gold bars, placed between the mirror and the streak camera, disperses the x-rays according to wavelength. (See Figure 7 for experimental data.)

mirror. The TGSS has been recognized by *Research and Development* magazine as one of the top 100 industrial inventions of 1985.

Altogether, both spectrometers represent a significant advance in our ability to measure soft-x-ray spectra. Our x-ray laser experiments provided "the first absolutely incontrovertible evidence" of the production of a macroscopic, high-gain amplification medium for soft x-rays. Collection of this evidence was made possible, in large part, by our innovative diagnostics.

4) The experiments

During 1984, we performed more than 100 separate experiments in which we irradiated x-ray laser targets with Novette's two beams [**Figure 5**]. The 0.53-μm [green] laser light, frequency-doubled from Novette's fundamental [1.05-μm] harmonic, was focused by a cylindrical lens to a region of the foil 1.2 cm long by 0.02 cm wide. The foil exploded as the laser burned through it, creating a fairly uniform electron density in the plasma, which expanded into a roughly cylindrical shape. The uniform density enabled the beam of the x-ray laser to proceed straight down the long axis of the foil, staying within the high-gain region and propagating into the narrow angle of acceptance of the diagnostics.

Targets were irradiated in two different geometries: single-sided, in which a segment of the foil was illuminated with only one laser beam, and double-sided, in which opposing laser beams irradiated a common target area.

We used the double-sided configuration in an attempt to compensate for random nonuniformities in a single beam that could lead to refractory inhomogeneities in the density of the lasing medium. We found, however, that since a single beam exploded the foil almost symmetrically, the beam profile was sufficiently smooth to make this an acceptable, although not preferred, illumination scheme.

Our measurement strategy was to vary the thickness of the selenium foil from 75 to 300 nm and optical-laser irradiance from 1.2×10^{13} to 2.5×10^{14} W/cm^2 at pulse lengths of 120 to 750 ps, values that bounded our basic theoretical design. We searched for neon-like transitions that were brighter and briefer than nearby spontaneous emission lines and that showed strong angular anisotropy when viewed both on and off axis. In addition, we measured the variation of brightness with length, a rough index of amplification. This overall approach was distinctive inasmuch as we were not forced to rely on any one criterion of lasing action.

The results conclusively demonstrated, for the first time, amplification at short wavelengths. We observed amplification of at least four $3p$ to $3s$ transitions, the largest gain being detected for the $J = 2$ to $J = 1$ lines at wavelengths of 20.9 nm (59 eV) and 20.6 nm (60 eV) in selenium and at 15.5 nm (80 eV) in yttrium. The last is the shortest wavelength at which significant amplification has ever been produced in the laboratory. By varying the length of the selenium targets, we were able to observe the exponential growth with increasing

Figure 5
Schematic of x-ray laser diagnostic

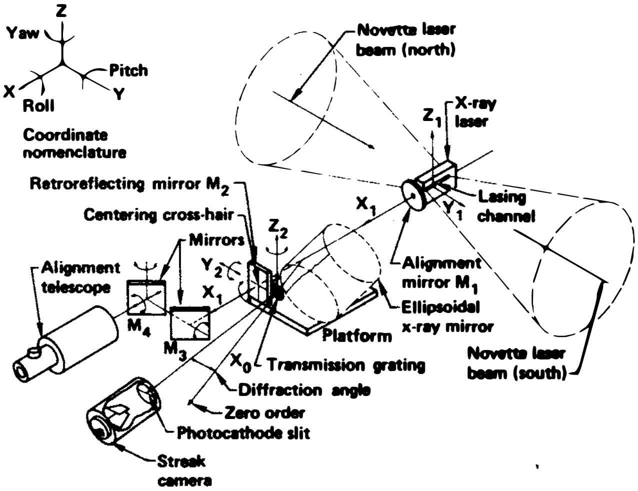


Diagram of x-ray laser experiment with two-sided laser irradiation of selenium x-ray lasing foil. An anvil (x-ray laser) holds the selenium foil in place with openings on both sides (lasing channel) for irradiation by the two-beam Novette optical laser (Novette laser beam, north and south). An alignment mirror M_1 permits the anvil to be located with extreme accuracy.

length that characterizes stimulated emission.

With the selenium targets, we found that optimum amplification occurred at a target thickness of 75 nm, a pulse length of 450 ps or longer, and irradiances of about 5×10^{13} W/cm^2 for double-sided irradiation. Because of the limited range of parameter space explored, however, it is unlikely that these values represent the ultimate performance of this type of amplifier.

We also were able to verify the strong anisotropy of emission lines. **Figure 6** shows both film data and spectral representations of typical time segments monitored by the microchannel-plate grazing-incidence spectrometer. Sodium-like transitions in selenium, which are not amplified, are visible both on and off axis, whereas the strong transitions at 20.6 and 20.9 nm can be seen only on axis.

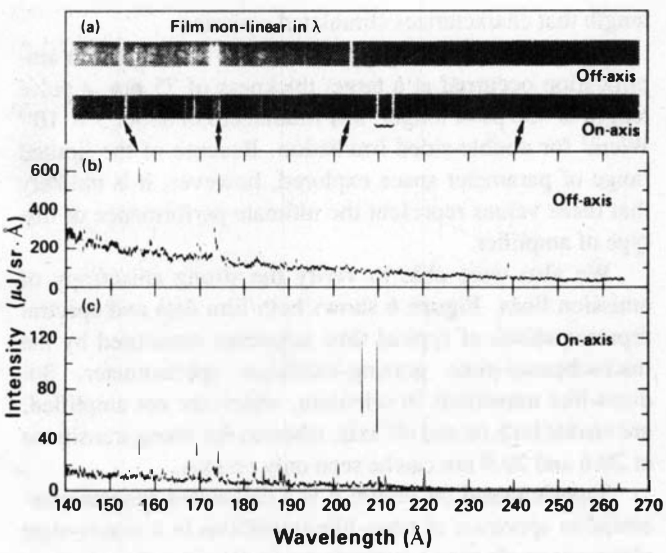
Superimposed on Figure 6 is a calculated spontaneous-emission spectrum of neon-like transitions in a steady-state plasma at an electron temperature of 1.0 keV and an electron density of $10^{21}/cm^3$. The observed 20.6- and 20.9-nm lines, recorded here at less than maximum intensity, are much stronger than all of the other nonlasing, neon-like transitions, some of which have larger unamplified values These two lines dominated the spectrum in about 100 laser shots, and their intensity increased with the length of the foil targets.

Figure 7, a time-resolved spectrum obtained with the transmission-grating streak spectrometer, demonstrates the maximum amplification achieved. In this single-sided shot, the two laser beams were displaced to give a total amplification length of 2.2 cm. The amplification is so intense that the filtration necessary to keep the signal within the instrument's dynamic range almost eliminates the background spectrum. The very intense emissions at 20.6 and 20.9 nm are a strong indication of nonequilibrium conditions in the plasma. Assuming that the width of the Doppler-broadened line at 20.6 nm is 0.004 nm and given the measured source area of 200 μm diameter, we obtain an equivalent radiation temperature of between 30 and 50 keV. In contrast, the brightness temperature of the sodium-like nonlasing line at 20.1 nm is only 0.1 keV.

5) Conclusions

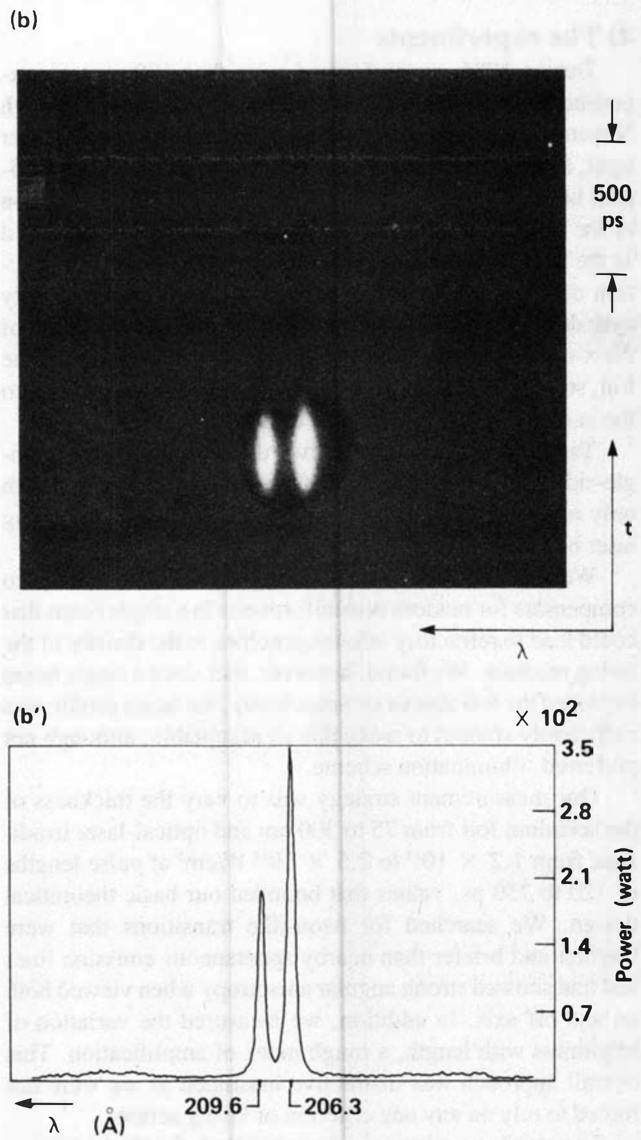
Using an optical laser to produce a population inversion in an exploding-foil plasma, we have demonstrated substantial amplification of spontaneous emission at soft-x-ray wavelengths. Scaling the experiments to even shorter x-ray wavelengths seems straightforward up to the power limit of the driving laser. The feasibility of such scaling was demonstrated by our experiments with yttrium targets, where we demonstrated amplification of the same $J = 2$ to $J = 1$ lines at 15.5 nm. Future experiments will include foils of higher-Z elements, whose inner electrons are more tightly bound and therefore capable of more energetic lasing transitions. It is estimated that lasing at wavelengths as short as 8 nm is attainable with the collisional excitation scheme, although a price will be paid in terms of lower gain. Current targets provide unsaturated, single-pass amplification; we plan to saturate gain and improve energy output by adding a resonant

Figure 6
Some lines are only observed in axial spectrograph



The experimental measurements by the MCPIGS (see Figure 3). The lines on the film provide measures of both the wavelength and intensity of the radiation emitted from the plasma. When the MCPIGS is aligned "off-axis"—that is, not along the line defined by the axis of the x-ray laser—the two x-ray lasing transitions, 20.6 and 20.9 nm (206 and 209 angstroms) are not seen. But when aligned along the x-ray laser axis, the two x-ray lasing transitions are very strong.

Figure 7



The TGSS measurements of the selenium x-ray laser (see Figure 4). At the top is the actual streak camera film during the x-ray laser experiment. The graph at the bottom shows that the selenium x-ray lasing transitions, at 206 and 209 angstroms (20.6 and 20.9 nm respectively), seen on the film are well above the background thermal radiation. The streak camera film also shows that the x-ray laser pulse duration is less than that of the incident Novette optical laser pulses.

cavity or by focusing the plasma-generating laser beam over a greater target length.

Now that we have indeed demonstrated lasing at soft-x-ray wavelengths, we must next refine the technology and build a fuller understanding of our current x-ray lasing scheme. Toward this end, we have identified five major tasks on which we will concentrate our efforts in the next year or so:

- quantitatively characterizing the ionization balance and inversion kinetics in exploding-foil x-ray laser targets
- achieving a saturated, well-characterized x-ray amplifier at wavelengths of 20.6 and 20.9 nm (those observed with the selenium targets)
- demonstrating amplification at shorter wavelengths[1]
- developing a multipass x-ray laser cavity [oscillator][2,3,4]
- illustrating significant applications.

The new experimental campaign began in October 1985. Our experiments are the first in a facility designed to accommodate two of the ten laser beams on the Laboratory's powerful new Nova laser. (The target chamber is the same used in the original soft-x-ray experiments conducted with the Novette laser.) To diagnose these experiments, we will field an improved array of instruments. Altogether, this expanded effort promises to make important contributions to our understanding of the physics of x-ray lasers.

Potential Applications. In mid-February of this year, about three dozen scientists in a variety of disciplines ranging from microbiology to solid-state physics gathered for three days at the Asilomar Conference Center in Monterey, California to discuss potential applications of the x-ray laser. This international meeting sponsored and organized by Lawrence Livermore National Laboratory, provided a unique forum for the cross-disciplinary exchange of ideas and opinions about how best to exploit the fledgling x-ray laser technology. Not surprisingly, the occasion produced valuable suggestions, new insights, and some lively debate. By the close, several lines of promising directions for future work had emerged.

For example, the technology may have a role in the microscopy of biological structures, especially if the operating wavelength can be shortened below 4.4 nm. The dramatic differences between x-ray and electron micrographs of biological structures clearly indicate that a mature technology of x-ray microscopy may provide a whole new perspective to the field. Current electron-microscopy techniques require sectioning specimens or treating them with metallic fixitives. Holographic imaging at x-ray wavelengths, in contrast, could record *in vitro* structures with high resolution in three dimensions. (Although the intensity of the x-radiation would kill tissue, recording would be fast enough to preserve an image.)

In micromechanics, a well-characterized source of coherent x-rays could be used to produce high-resolution diffraction gratings with periodic spacings significantly smaller than those now attainable. Coherent sources of soft x-rays can also prove valuable for applications that depend on interference effects.

Detailed knowledge of the chemical and physical properties of solid surfaces is essential to the control of many surface processes such as catalysis, crystal growth, oxidation, corrosion, and microelectronic-device fabrication. The newly emerging discipline of high-resolution, time-resolved photoemission spectroscopy is helping us make great strides in understanding the physical structure and electronic-state distribution at the solid-state surface. However, advances in this field are currently limited by the availability of appropriate sources of short-wavelength, monochromatic radiation. An x-ray laser with a high repetition rate, good mode quality, turnability, and very short pulses (less than 10^{-12}s) could significantly expand research in this area.

Summary. Our current experimental campaign, being conducted at the new two-beam Nova facility, has several important goals. First, we are seeking a better understanding of the physics of the x-ray laser in order to predict experimental results more accurately and perhaps to suggest new techniques for producing population inversions. A major effort also will be focused on optimizing the gain and efficiency of our selenium and yttrium targets. We hope to saturate output at about 10 MW per emission line. We will also conduct experiments designed to demonstrate the feasibility of a multipass amplifier consisting of multilayer mirrors. Another important goal will be to demonstrate lasing at even shorter wavelengths using targets of higher atomic number. Finally, we will explore a variety of applications of the soft-x-ray laser, including measurements of the coherence and divergence of the laser beam, the generation of holographic images, x-ray microscopy, and the susceptibility of various materials to x-ray damage. As the technology develops in directions more adapted to the needs of specific applications, it can also be expected to stimulate new approaches to current and future research problems.

References for further reading

This is a representative selection of papers from the scientific literature on x-ray lasers and the Livermore experiments.

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