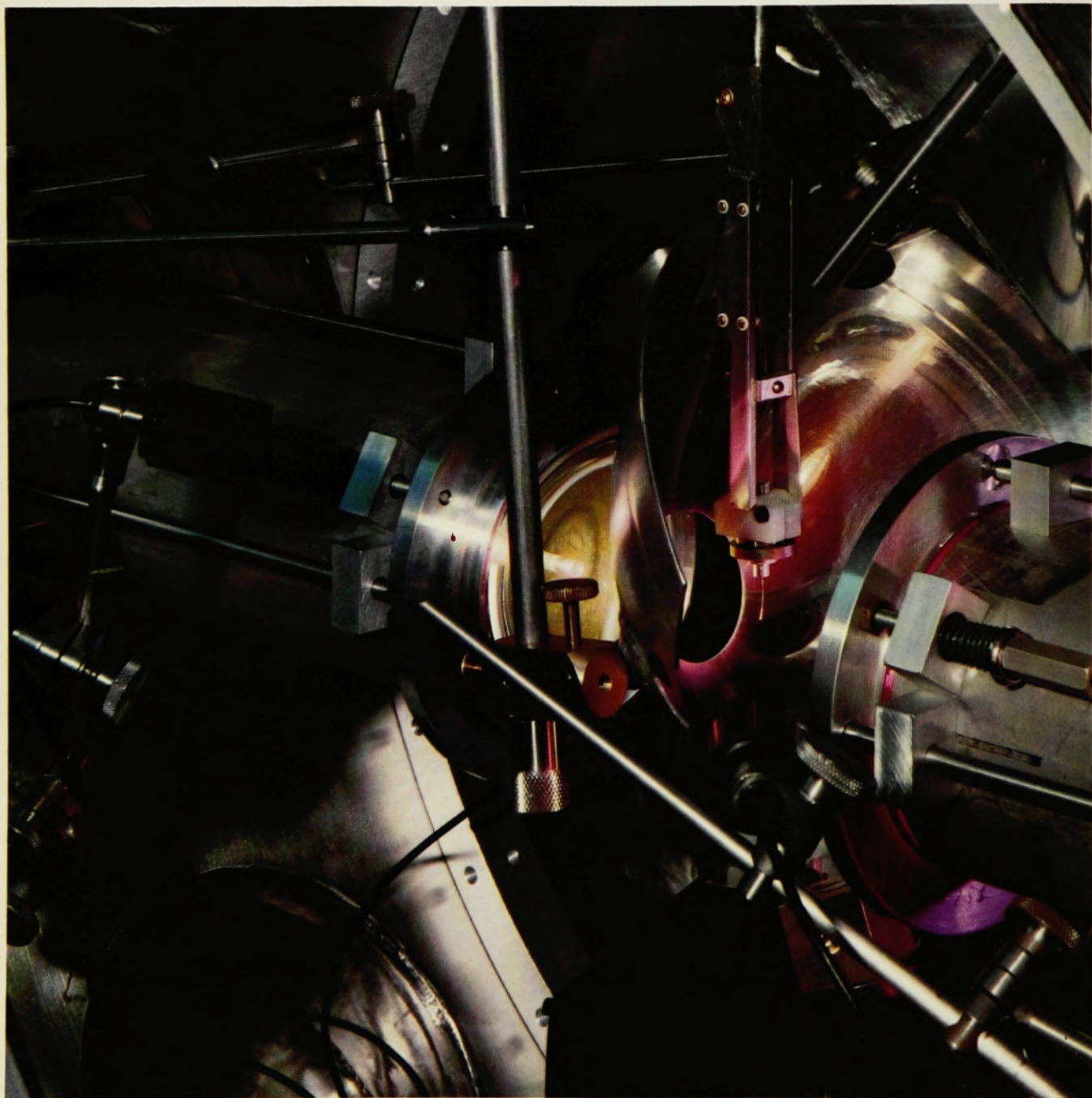


X-ray lasers

George Chapline and Lowell Wood



The target-positioning system centered in the vacuum chamber and surrounded by diagnostic equipment is used in ultrahigh-intensity laser-irradiation experiments. It is part of the Janus laser system at the

Lawrence Livermore Laboratory, which is currently being used for laser fusion experiments and which is also slated for x-ray laser experiments such as those discussed in this article.

Figure 1

Experiments with high-power lasers may soon demonstrate stimulated emission of x rays; future devices could have far-reaching impacts on chemistry, biology and crystallography.

One of the great barriers to improving our understanding of the molecular basis of life is that we do not yet have any way of examining individual macromolecules in living tissue. The progress made so far in unravelling the *structures* of biological macromolecules is based on painstaking chemical and x-ray crystallographic analyses of pure, crystalline samples of a given macromolecule.¹ This situation could, however, be completely revolutionized if a source of coherent x rays were available. Although, as we shall show below, the realization of this goal is beset with difficulties, experiments aimed towards its accomplishments are under way, as shown in figure 1.

To resolve the structure of molecules one needs radiation of wavelength comparable to the size of atoms. In practice, this means that one must use photons with energies of at least a few kilovolts (that is, x rays) or electrons with energies over a hundred kilovolts (see "Search and Discovery," PHYSICS TODAY, May 1974). The use of x rays—as an illuminating source has the advantages that no vacuum enveloping the sample is required, and that the sample suffers much less radiation damage in the process. In particular, by using x rays one should be able to study macromolecules in living tissues, thereby gaining crucial insights into cellular functions. The reason this has not yet been done is that the index of refraction of low-*Z* elements is close to unity throughout the x-ray region, and therefore targets containing low-*Z* elements offer poor image contrast when illuminated with ordinary x-ray sources. A source of *coherent* x-rays, on the other hand, would make phase-contrast microscopy possible, which would yield contrasts sufficiently high to allow the

study of biological macromolecules *in situ*. A coherent x-ray source would, in fact, permit one to make three-dimensional holograms of important biological structures, such as the DNA in a cell nucleus (see figure 2). Using this technique one could, for example, make three-dimensional motion pictures—with atom-scale resolution—of the replication of DNA, ribosomal synthesis of proteins and other important biological processes.

Coherent x rays would similarly provide a solution of the famous "phase problem" of x-ray crystallography.² To obtain the three-dimensional electron distribution in a crystal one has to know the relative phases as well as the amplitudes of the x rays scattered at different angles. With ordinary x-ray sources one can in general measure only the intensities, that is, the squares of the amplitudes of the scattered x rays. (The phases can often be determined by inspired guesswork and clever tricks such as heavy-atom substitutions, together with very extensive use of digital computers to calculate the implications of the iterated guesses. However, such techniques are in general useful only for structure elucidation of crystals containing molecules of molecular weight less than about 10^5 , which is one or two orders of magnitude below that of many biologically crucial molecules such as the large nucleic-acid polymers.) The determination of the atomic structure is now a special problem for every material, and a number of Nobel prizes have been awarded for deciphering particular materials. By contrast, determination of the relative *phases* of the scattered waves would also be straightforward if a coherent source of x rays were available—this would make the determination of the atomic-scale architecture of even the largest molecules a routine matter.

A further possible benefit of using coherent x rays to study materials is that very short (about 10^{-15} sec) x-ray pulses might be attainable with these sources, so that one could "freeze" molecular vibrations. Indeed, the possi-

bility would then exist of watching, in slow motion, thermal vibrations—even shock-wave compressions—in various materials.

What prospects?

It is clear from all this that a coherent source of x rays would have revolutionary implications for many areas of biology, chemistry, physics and materials science. What, then, are the prospects for generating these coherent x rays? There has been a great deal of interest during the past few years in the possibility of generating coherent x rays via an x-ray laser, due in part to several suggestions as to how this might be realized³⁻⁷ and in part to the development of pumping sources that might suffice for pumping an x-ray laser system. This interest was greatly stimulated when workers at the University of Utah reported⁸ that coherent x rays were emitted when a pulse from a neodymium-glass laser was focussed onto a thin layer of gelatin containing a dilute solution of CuSO_4 . This claim of having produced x-ray laser action was, however, based on observations of spots on x-ray film that were subsequently shown to have not been produced by x rays at all.⁹ Indeed, it was soon realized that true x-ray laser action was probably impossible to achieve with lasers then (*circa* 1973) existing.

Development of x-ray lasers has not yet occurred because favorable conditions for lasing are extremely difficult to attain at x-ray wavelengths. In the first place, cold matter is highly opaque at all x-ray wavelengths, due to photoelectric absorption. The nearest analog to a transparent optical laser medium (such as glass) at x-ray wavelengths is a completely ionized high-temperature plasma. Secondly, very high pumping powers are required to maintain the population inversions necessary for laser action, because of the very short excited-state lifetimes and the higher transition energies involved. The lifetimes for allowed x-ray transitions are of the order of $10^{-15} \lambda_A^2$ sec, where λ_A is the wavelength in angstroms. There-

The authors are staff members of the physics department of the University of California's Lawrence Livermore Laboratory. Chapline leads the theoretical studies effort, and Wood is the program manager, of the Laboratory's x-ray laser program.

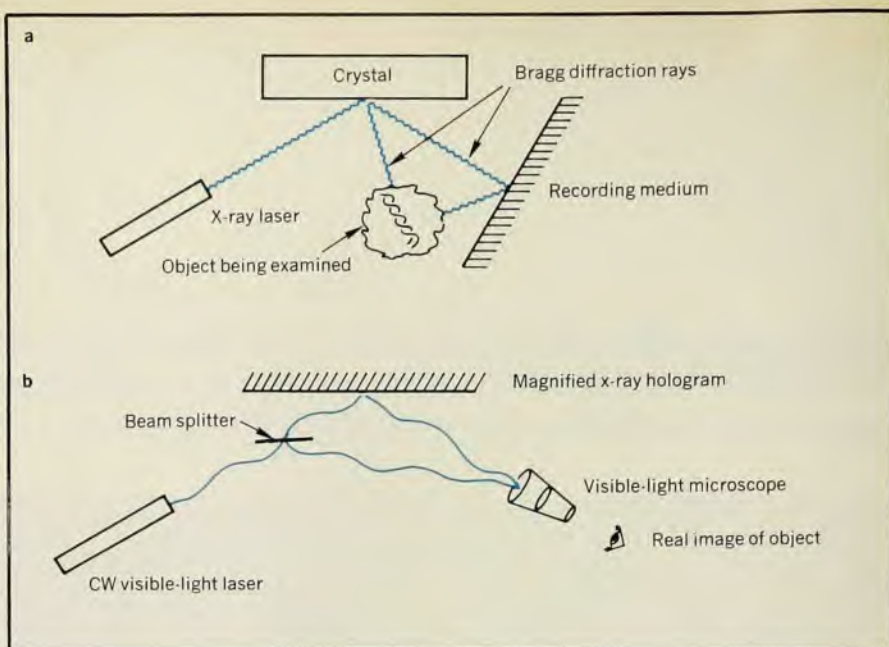
fore a 10-kilovolt transition ($\lambda = 1.2 \text{ \AA}$) has a radiative lifetime of the order of 10^{-15} sec, so to keep an atom with such a transition in its excited state, one must supply a pumping energy of the order of one watt per atom! Clearly, operation of an x-ray laser will require enormous pumping powers, and it is really only with the ultrahigh-power lasers now being developed that one could hope to produce the power densities required.

Another barrier to the demonstration of lasing action at x-ray wavelengths arises from the fact that an x-ray laser must probably be operated without external mirrors, due to the low reflectivity of materials when $\lambda < 1000 \text{ \AA}$. It has been suggested that instead of using mirrors one might circulate the beam around a circuit, using arrangements of Bragg-angle reflectors¹⁰ but, again, absorption of x-rays at the reflectors strongly erodes the usefulness of this type of scheme. This proposal to run the x-ray pulse around the Bragg-reflector loop even once, also involves times long compared to x-ray radiative lifetimes. In an ordinary laser, the light bounces back and forth between the mirrors, stimulating emission of light from the atoms that have been pumped to the excited state. In the absence of mirrors, one must have a longer laser medium to make up for the lack of round trips between mirrors. This means that substantially larger gains down the length of the laser medium are required if mirrors cannot be used—the exact gain required to produce substantial laser action without mirrors will depend on diffraction losses and the destruction rates of the excited states.¹¹ For a 1-kilovolt x-ray laser the length, l , of the laser medium must be such that the gain down the length of the laser medium is of the order of a hundred dB; that is,

$$\alpha l \gtrsim 20 \quad (1)$$

where α is the small-signal gain per unit length. At the same time the gain across the smaller dimensions of the laser must be kept small enough to avoid substantial radial stimulated emission. The diameter of the laser medium therefore must be small compared to its length, and so the medium must be in the form of a thin cylinder.

It turns out the length l needed to satisfy equation 1 will in practice always exceed $c\tau_{\text{spont}}$, where c is the speed of light and τ_{spont} is the spontaneous radiative lifetime of the x-ray laser transition. Thus, in general, it will be necessary to use "traveling-wave" excitation to pump the medium, to optimize pumping efficiency. One may picture the operation of an x-ray laser as consisting of the sweep of a suitable pumping excitation along the cylindrical medium at the speed of light; a growing



This scheme for obtaining three-dimensional pictures of macromolecules in living matter with x-ray phase-contrast holography is one possible application of an x-ray laser. Diagram **a** shows the recording of the hologram and **b** indicates the way in which a visible image, magnified by the ratio of the wavelength of visible light to that of x rays, is formed. Figure 2

pulse of coherent x radiation will accompany this traveling excitation wave if a sufficiently large population-inversion density has been attained. A schematic diagram of the form an x-ray laser might take is shown in figure 3.

Pumping requirements

In their classic 1958 paper on the operation of a laser, Arthur Schawlow and Charles Townes showed that a certain threshold inversion density must be achieved to produce laser action. The analogue of their threshold condition for a laser operating without mirrors is $\alpha l \approx 1$. In the absence of losses α is given by

$$\alpha = \left(N_2 - \frac{g_2}{g_1} N_1 \right) \frac{\lambda^2}{8\pi} \frac{1}{\tau_{\text{spont}} \Delta\nu} \quad (2)$$

where N_2 is the population of the upper state, N_1 is the population of the lower state, g_1 and g_2 are the statistical weights of the states and $\Delta\nu$ is the bandwidth of the lasing transition. Since the spontaneous radiative lifetime τ_{spont} of allowed transitions varies as λ^2 , it is clear from equation 2 that the threshold inversion density will depend only on the bandwidth $\Delta\nu$ and the length l . Taking into account the fact that one must operate somewhat above threshold to obtain significant stimulated emission (that is, $\alpha l \gtrsim 20$), one finds that the population inversion must satisfy:

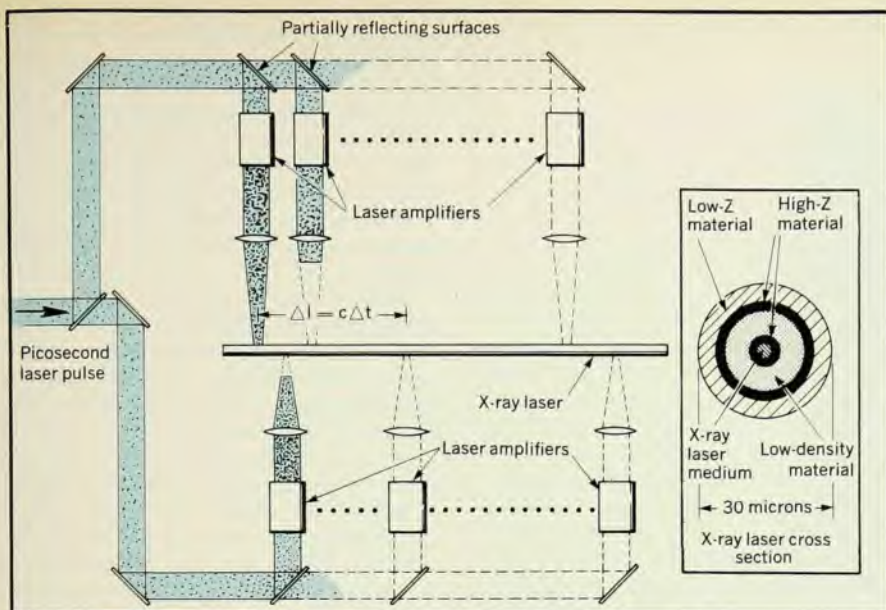
$$N^* \gtrsim (\Delta\nu/l) 10^{18} \text{ cm}^{-3} \quad (3)$$

where $N^* \equiv N_2 - (g_2/g_1) N_1$ is the effective population-inversion density, and $\Delta\nu$ is in electron volts and l in cm.

In cold matter, the width determined by the Auger effect (about 1 eV) fixes a lower bound on the inversion density needed for laser action. This inversion density is necessarily very high, as is evident from equation 3 and, since the Auger width corresponds to a lifetime of about 10^{-15} sec, this implies that enormous pumping power densities will be needed to maintain required population inversions in cold matter. Furthermore, condition 3 may not be sufficient for laser action in a cold medium because the inversion density must be large enough to overcome the large photoelectric opacity of cold matter.

In hot matter, the minimum inversion density will be determined by the Stark width; Doppler broadening will be less important in most circumstances. Estimates¹² of the Stark width in a solid-density plasma containing identical, almost fully stripped ions leads to $N^*_{\text{min}} \approx 5 \times 10^{19}/l \text{ cm}^{-3}$. For $l = 1 \text{ cm}$, this corresponds to a fractional inversion $N^*/N \approx 10^{-3}$, where N is the total atomic density. If the fractional inversion turns out to be smaller than 10^{-3} , then either medium densities higher than solid densities or lengths $l > 1 \text{ cm}$ would be required for lasing. To utilize inversion densities low enough to be comparable to plasma densities available from conventional sources such as ion beams, it is clear that high fractional inversion densities, greater than 0.1, would have to be achieved.

Since the energy needed to produce a population inversion, $h\nu N^* d^2 l$, must be supplied in a time l/c , the pumping power required to operate the x-ray



A conceptual design for an x-ray laser. A picosecond laser pulse from a master oscillator–preamplifier chain is fed in portions, via beamsplitters and final amplifiers, onto the x-ray laser target axis. The pulses are sequenced to cause an ultrastrong heating wave to move down axis with the speed of light. The concentric cylindrical target (inset) focusses radial shocks onto the x-ray laser medium to produce the inner-shell vacancies needed.

Figure 3

laser is given by the relationship

$$P_{\text{pump}} = h\nu N^* d^2 c / \epsilon \quad (4)$$

where ϵ is the pumping efficiency. Obviously one will want to make d as small as possible. One cannot make d much smaller than $\sqrt{\lambda l}$, however, because diffraction losses would then become severe. Assuming that $d^2 = \lambda l$, $\Delta\nu = 1$ eV, and $\epsilon = 10^{-3}$ (a value that detailed studies indicate is characteristic), we find that the minimum power required is 1 gigawatt. This power level is well within the capabilities of present-day laser systems. However, before one concludes that existing lasers are capable of pumping an x-ray laser, it should be pointed out that it will not in general be possible to focus a high-power laser pulse onto a target with diameter $\sqrt{\lambda l}$; nor is it necessarily possible to sweep a focused beam along an x-ray laser medium in such a way as to produce an optimal traveling-wave excitation. A more realistic appraisal of the pumping requirements in fact suggest that a 10^{12} -watt laser would be needed to pump a 1-kilovolt x-ray laser. Fortunately, 10^{12} -W lasers are just coming to within the state of the art, and therefore meaningful experiments aimed at producing lasing action at $\lambda \approx 10$ Å may soon be possible.

Possibilities

What atomic states will give suitable transitions? To produce x rays with $\lambda < 100$ Å, we require atomic numbers greater than 4 for K_α radiation and greater than 8 for L_α radiation. Transitions between states of high principal

quantum number or between subshells, such as $3s \rightarrow 3p$, have the disadvantage that such transitions require high values of Z to produce x rays, and these would lead to relatively large photoelectric losses. Further, states of high principal quantum number and distinct subshells will not exist at the high densities that appear to be required for an x-ray laser medium, because of continuum lowering and Stark mixing of states respectively. From a point of view encompassing oscillator strength, Stark broadening and photoelectric loss, the utilization of inner shell-transitions is favored. On the other hand, population inversions will probably be quenched rather rapidly if the lower lasing state is the ionic ground state, because of the comparatively very large recombination rates into this state. The most promising transitions for x-ray lasers therefore appear to be M-shell $\rightarrow$ L-shell transitions in nearly fully stripped, moderate- Z ions. For example, $3 \rightarrow 2$ transition in hydrogen-like krypton may be a useful transition for demonstrating x-ray lasing action; see figure 4.

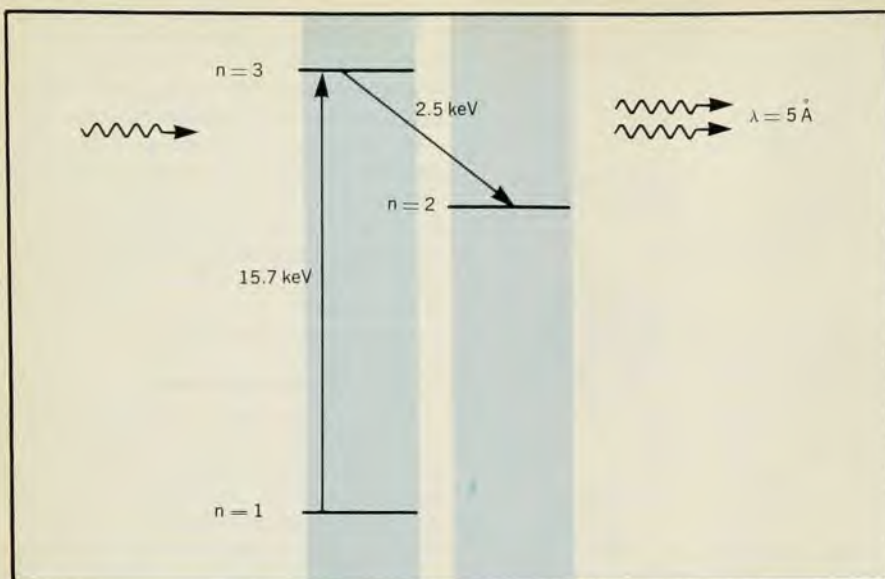
Because of the very short lifetimes of allowed x-ray transitions (10^{-13} sec for 1-keV transitions), one might think that it would be more convenient to use metastable states in an x-ray laser. Metastable states of two- and three-electron ions with lifetimes of the order of 10^{-9} sec have been observed in low-density ion beams.¹³ However, these metastable states are unlikely to be very long-lived at the relatively high densities required for even a metastable me-

dium, because of Stark mixing into allowed transition states as well as triplet-triplet annihilation processes. Furthermore, even if metastable states could somehow be prepared at the necessary high densities, the gain per unit length attainable with these metastable states would be very low compared to that attainable with allowed transitions—see equation 2. Thus, either impractically high inversion densities or inconveniently great lengths would be needed for metastable-state lasers.

Population-inverting schemes

The problems of producing population inversions in the x-ray region are very different from those at lower photon energies. In the infrared, visible, and near-ultraviolet regions one must deal with the complexities of molecular or solid-state kinetics. While these complexities provide many opportunities for lasing, they also make theoretical calculations difficult and unreliable. X-ray transitions, on the other hand, occur between tightly bound states where the processes affecting level populations are quite well understood. These processes include photoionization and radiative recombination, Auger ejection and dielectronic recombination, electron collisional excitation and de-excitation, ionic collision processes, and charge exchange. Since x-ray transitions take place between states with wavefunctions that are nearly hydrogenic, the cross sections and rate coefficients for these processes can be calculated with reasonable accuracy. These considerations suggest that detailed theoretical calculations of the changes in electronic level populations due to the above processes may be very useful in evaluating the feasibility of x-ray laser pumping schemes, and such calculations are central to our own efforts to produce x-ray lasing action. Although completely detailed calculations have yet to be carried out on any such pumping scheme, it appears that there are a number of situations in which the processes mentioned could lead to population inversions for x-ray transitions.

For example, population inversions could be produced in a straightforward way by exposing a target to an x-ray flash of very high intensity.³ A population inversion would be created because, for wavelengths in the x-ray region, the probability for photoionization of a tightly bound electron is several times larger than that for a loosely bound electron. Unfortunately, conventional flash x-ray sources are not nearly bright enough to produce the needed high inversion densities on the time scales required. Assuming that the lifetime of the inverted state is 10^{-15} sec (the Auger lifetime), pumping a 1-keV transition requires 10^{16} W/cm² for a target 10 microns thick. However,



Hydrogenlike krypton provides a possible x-ray laser transition, with a spontaneous radiative lifetime of about 10^{-14} sec and a cross section of about 10^{-18} cm² for stimulated emission. Lasers powerful enough to provide the needed pumping are not yet available. Figure 4

presently available flash x-ray machines cannot produce x-ray intensities much higher than about 10^{10} W/cm².

It might be possible, however, to produce an x-ray pumping pulse of the required brightness by focusing a high-energy laser pulse onto a high-Z target.¹⁴ The efficiency of converting laser light into x-rays at appropriate energies is unknown at very high laser intensities, but even if it were as large as 1%, a laser intensity of 10^{18} W/cm² would be required. Such an intensity could be generated by focussing a 10^{12} -W laser pulse onto a spot 10 microns across. Such a focussed laser intensity may be achievable in the near future but, as mentioned, we have little idea of what the x-ray conversion efficiencies are at such an intensity.

Another problem with this type of x-ray pumping scheme is the ultrashort rise times required in view of the characteristic decay time for excited states (the Auger lifetime) of 10^{-15} sec. It has been suggested that a quasistationary population inversion can be maintained as long as the lower state of the lasing transition decays faster than the radiative lifetime, but calculations carried out by Timothy Axelrod have shown that, when all Auger processes and the heating of the medium are taken into account, such population inversions do not last longer than about 10^{-14} sec. This time is much shorter than the rise time of any high-power laser pulse that is likely to be available in the near future. Thus the prospects for this type of x-ray laser pumping do not appear promising for the near term.

Selective ionization of a particular inner shell might also be accomplished with energetic ions. For example, when

two atoms of moderate atomic number collide energetically with sufficiently small impact parameter, the Pauli exclusion principle requires the ejection of one or more electrons from one or the other of the atoms of the quasi-molecule transiently formed, at the expense of the kinetic energy of the colliding atoms. When two inner-shell energy levels in the colliding atoms are reasonably well matched, the collision will lead to selective production of vacancies in these shells. The possibility of using this process to achieve lasing at x-ray wavelengths was first discussed by R. A. McCorkle,⁷ who proposed sweeping a high-current ion beam along a thin foil at the speed of light. Unfortunately, the gains attainable with this particular scheme are very small, due both to the very limited densities attainable with ion beams and to severe diffraction losses.

It is possible that usefully large gains per unit length could be attained by this process with charge-neutralized beams. For example, David Cheng has demonstrated in experiments at Ames Research Laboratory that charge-neutralized beams of argon ions with kinetic energies exceeding 10 keV and densities greater than 10^{18} cm⁻³ are attainable.¹⁶ A fundamental difficulty with these approaches, however, is that the rise times for ion beams are orders of magnitude longer than typical x-ray-coupled population inversion lifetimes. A way around these difficulties might be to produce a very strong cylindrically imploding shock in a small fiber, with shock velocities of 10^8 cm/sec in condensed media. If the fiber were dense enough ($\rho \approx \rho_{\text{solid}}$), then the rise time for inner-shell vacancies due ion-ion

collisions in the shock would be much less than 10^{-12} and could be comparable to the inversion lifetime. One possible approach to attainment of such conditions would be to strongly shock-heat a low-density fiber by supersonically penetrating a surrounding material of higher density with a thermal wave engendered by a short-duration laser pulse.

Rather than attempting to eject electrons preferentially from a given inner shell by quasi-stationary ionization processes, one might consider trying to create population inversions by forcing electrons to recombine with stripped ions into particular preferred states. If, for example, one cooled a dense plasma on a time scale short compared to radiative lifetimes, one might then be able to make use of the fact that collisional recombination of electrons into upper electronic levels is faster at high densities than radiative recombination into lower levels. One possible way to cool a thin x-ray laser medium would be to bring it into contact with a high-Z radiator. However, the pumping powers for this type of scheme are similar to those required for breakeven laser-induced fusion, since radiative cooling rates of the order required (about 1 watt/atom) can only be attained with laser powers $\approx 10^{15}$ W.

Instead of using thermal cooling one might also consider using resonant charge exchange to produce population inversions in ions. A. V. Vinogradov and I. I. Sobel'man of the Lebedev Institute in Moscow have suggested⁶ that if a laser-heated plasma of moderate Z is allowed to expand into a cool helium atmosphere, population inversions could result from charge-exchange reactions between the helium atoms and the plasma ions. Another approach, actively being studied by Marlan Scully and co-workers at the University of Arizona, is the production of a 2p-1s population inversion in He⁺ by shooting an alpha-particle beam at a gas target.¹⁷ The complexity of these schemes makes them difficult to evaluate. Further, these charge-exchange schemes involve the production of relatively very soft x-rays ($\lambda \approx 300$ Å), and it is not clear that they can be extended to usefully short wavelengths.

As noted above, a 10^{12} -watt laser pulse might be adequate for pumping an x-ray laser transition of about 1 keV. The duration of the laser pulse will be determined by the requirement that the pumping pulse must be long enough to allow for propagation of the x-ray pulse. With the gains likely to be attainable, the x-ray laser medium will have to be at least 300 microns long, which implies that the effective duration of the pumping laser pulse must be greater than about 1 psec. At least one joule of laser light will be required for such a pulse.

Actually, 10^{12} -watt laser pulses of 100-psec duration are now available as a result of efforts under way around the world to demonstrate the feasibility of laser fusion.¹⁸ Thus x-ray lasers may come into being as a by-product of laser-fusion research.

Free-free x-ray lasers

Most of this discussion has centered on the use of transitions from one bound state to another for producing x-ray laser action, but we might also consider free-free transitions. Free-free transitions differ from bound-bound and free-bound transitions in that they do not have to occur in a charge-neutralized medium. For example, a relativistic beam of electrons could be forced to emit x-rays by passing the beam through a periodic electric or magnetic field.¹⁹ Because of the relativistic contraction effect, the wavelength of the radiation emitted by a beam of electrons, each with energy $\gamma m_e c^2$, where $\gamma = (1 - v^2/c^2)^{-1/2}$ and m_e is the electronic mass, will be the order of $(4\gamma^2)^{-1}$ times the spatial period of the electric or magnetic field. With a magnet period of 1 cm and a 5-GeV electron beam, for example, the wavelength of the emitted radiation would be 1 Å. A first step in this direction is the current effort of John Maday and William Fairbank at Stanford University to generate coherent optical radiation with a 20-MeV electron beam.

The generation of coherent x rays by running an electron beam through a periodic field makes use of the stimulated bremsstrahlung process. Coherent x rays might also, it has been suggested, be generated with stimulated Compton scattering.²⁰ Indeed, from the point of view of the Weizsäcker-Williams approximation, a stimulated bremsstrahlung laser is the same as a stimulated inverse Compton-scattering laser. The free-free laser analogue of the spontaneous radiative lifetime τ_{spont} is the time for spontaneous Compton scattering $\tau_C = (N_\gamma \sigma_T c)^{-1}$, where N_γ is the density of real photons in a stimulated Compton laser and the density of virtual photons in a stimulated bremsstrahlung laser, and σ_T is the Thomson cross section. The maximum density of either real or virtual photons that is easily attainable is about 10^{24} cm^{-3} so that, in practice, $\tau_C \geq 10^{-10} \text{ sec}$.

Since the scattering time is much longer than allowed lifetimes for bound-bound transitions, it would appear that the gain per unit length attainable with free-free transitions must be small. However, the large value of τ_{spont} for free-free transitions is offset by the fact that the effective line width $\Delta\nu$ for free-free transitions can be made fairly small. By using electron beams with well defined electron momenta ($\Delta p/p < 10^{-3}$) and an initial photon distribution

with a narrow spectral width, it should be possible to achieve $\Delta\nu \approx 10^{10} \text{ sec}^{-1}$. Thus the gain,

$$G_0 \approx N_e (\lambda^2 / 8\pi) (\Delta\nu \tau_{\text{spont}})^{-1}$$

$$G_0 \approx 10^{-15} N_e \lambda_A^2 \quad (5)$$

This relation shows that the principal barrier to a free-free x-ray laser will be the very high electron-beam densities needed. In terms of electron beam's current density, it is clear from equation 5 that beam current densities of the order of 10^7 amp/cm^2 would be required for a free-free x-ray laser of reasonable length. Candidate beams for a stimulated bremsstrahlung laser (such as the 20-GeV SLAC beam) do not have nearly high enough current densities. Pulsed electron-beam machines capable of producing 10^6 amp/cm^2 beams of 10-MeV electrons are, however, now available. These machines were the topic of an article by Hans H. Fleischmann in last month's issue of PHYSICS TODAY (page 34).

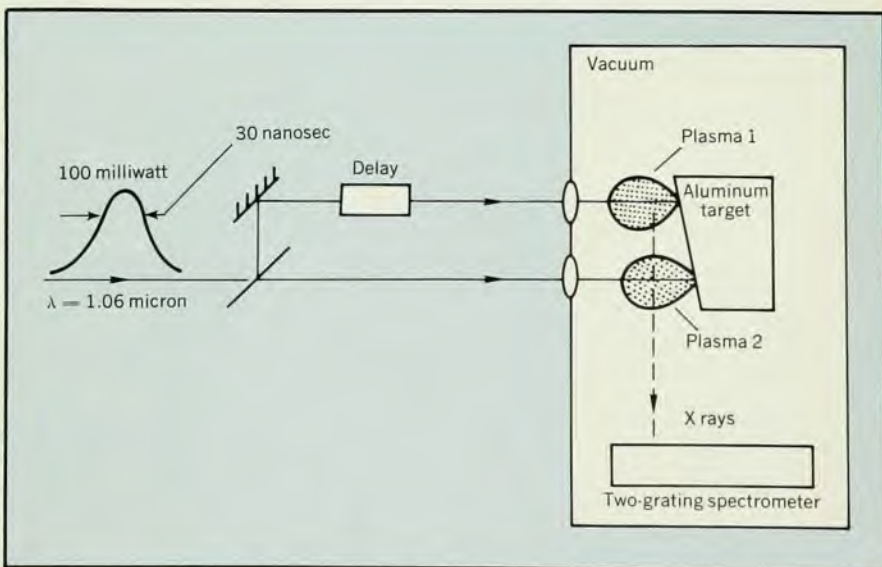
Experiments

Unfortunately, these high current densities are achieved in a pinched mode, for which calculations²¹ have indicated that the beam is quite "hot"—that is, $\Delta p \approx p$, necessitating beam-current densities of the order of 10^{10} amp/cm^2 for free-free x-ray lasers. There are, however, some indications that effective current densities of this magnitude can be attained with the Bennett fiber technique.²² If this is the case, a stimulated inverse Compton scattering laser may be within the realm of possibility.

At the present time, x-ray laser ex-

periments are being conducted at a number of laboratories around the world. To date, only one group—that of P. Jaegle at the Orsay Laboratories of the University of Paris²³—has offered even tentative evidence of stimulated emission at x-ray wavelengths. By looking at the x-ray emission of one laser-produced aluminum plasma through another laser-produced aluminum plasma, as shown in figure 5, they claim to have found evidence that a 117.4-Å line of Al^{3+} is amplified in passing through the second plasma. The inferred gain was 10 cm^{-1} , with a substantial uncertainty. The 117-Å line is due to $2p^5 4d^1 \rightarrow 2p^6$ transition. Both plasmas were produced on the same aluminum target by a 20-J, 40-nsec pulse from a neodymium-glass laser.

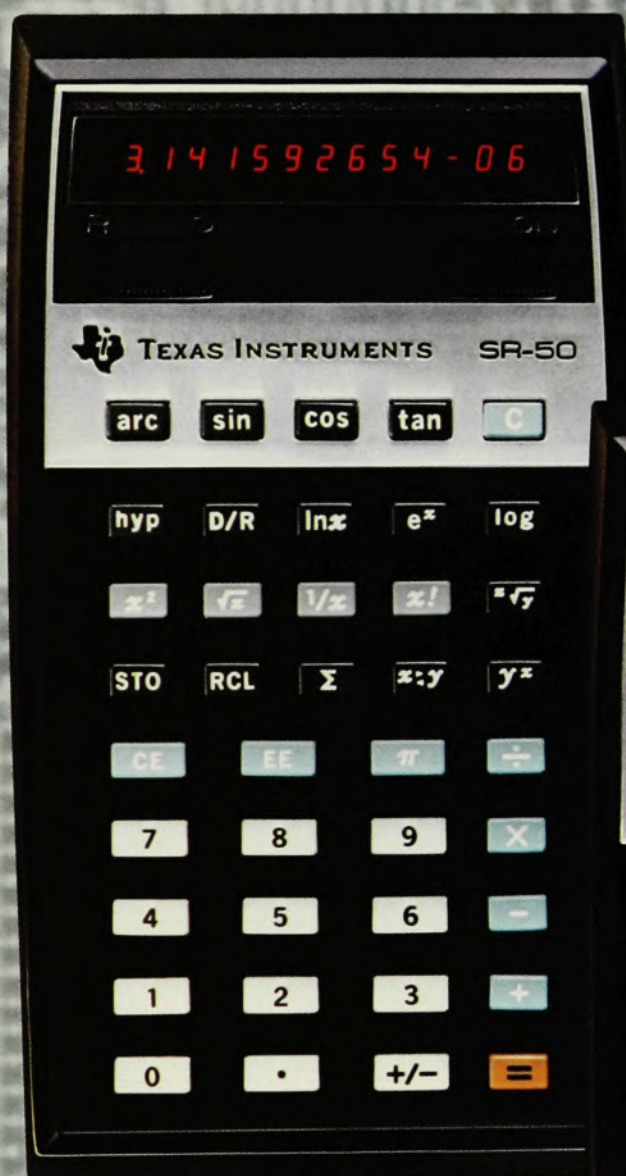
Since neodymium-glass lasers are the most convenient source of high-power pulses at the present time, most x-ray laser work has utilized these lasers. At the University of Rochester, a group led by James Forsyth and Moshe Lubin is studying the OVII and OVIII lines emitted by oxygen-doped LiD targets irradiated with a 10-psec pulse from a Nd-glass laser. At the Battelle Laboratories in Columbus, Ohio, Philip Mallozzi has studied the x-ray pumping of targets, using a laser-produced high-Z plasma as a source of x-rays. X-ray laser experiments using Nd lasers are also being carried out by Ron Andrews at the Naval Research Laboratories in Washington, and by Michel Duguay at the Sandia Laboratories in Albuquerque. Our own group at the Livermore Laboratory will soon begin x-ray laser work, using high-power Nd-glass lasers developed for laser-induced fusion experiments. The terawatt Cyclops laser system, to be used in these experiments,



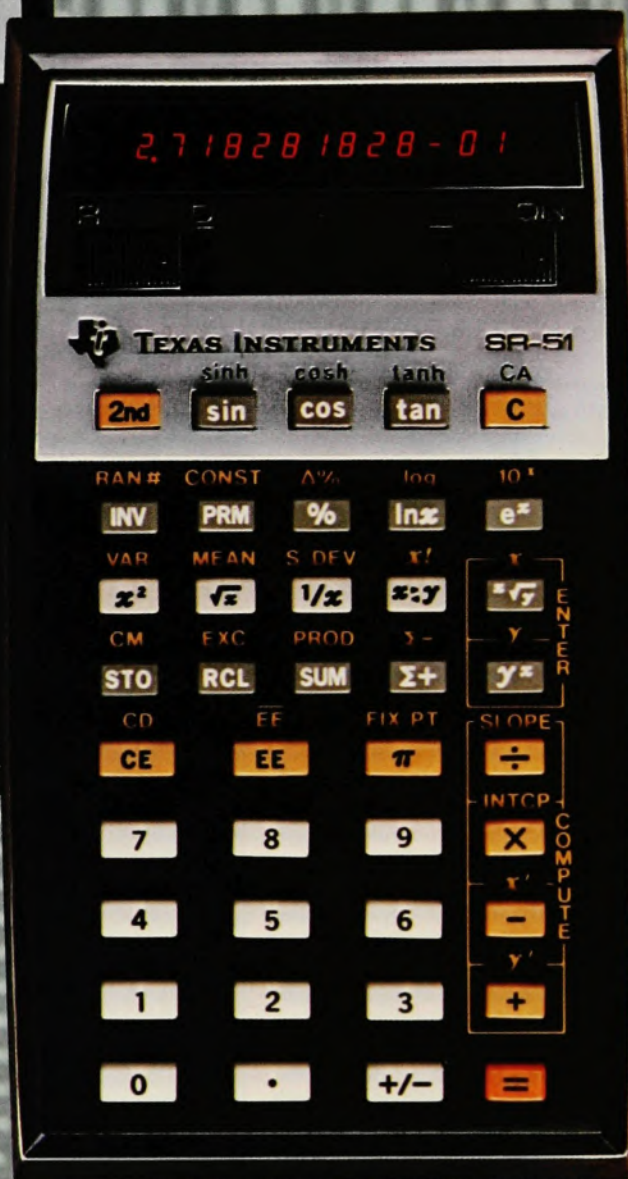
Orsay setup for measuring gain (or loss) of soft x-rays in aluminum plasma. A 20-joule pulse from a neodymium-glass laser produces two plasmas 40 microns apart; plasma 1 acts as the x-ray source, the other as the amplifying medium.

Figure 5

The SR-50. The SR-51.



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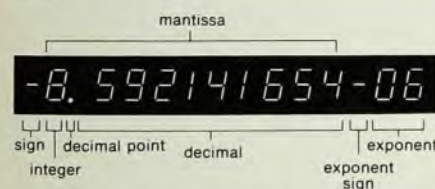
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FUNCTION	SR-51	SR-50
Log, ln x	yes	yes
Trig (sin, cos, tan, INV)	yes	yes
Hyperbolic (sinh, cosh, tanh, INV)	yes	yes
Degree-radian conversion	yes	yes
Deg/rad mode selection switch	yes	yes
Decimal degrees to deg. min. sec.	yes	no
Polar-rectangular conversion	yes	no
y^x	yes	yes
e^x	yes	yes
10^x	yes	no
x^2	yes	yes
$\sqrt{x}$	yes	yes
$\sqrt[y]{x}$	yes	yes
$1/x$	yes	yes
$x!$	yes	yes
Exchange x with y	yes	yes
Exchange x with memory	yes	no
% and Δ %	yes	no
Mean, variance and standard deviation	yes	no
Linear regression	yes	no
Trend line analysis	yes	no
Slope and intercept	yes	no
Store and sum to memory	yes	yes
Recall from memory	yes	yes
Product to memory	yes	no
Random number generator	yes	no
Automatic permutation	yes	no
Preprogrammed conversions	20	1
Digits accuracy	13	13
Algebraic notation (sum of products)	yes	yes
Memories	3	1
Fixed decimal option	yes	no
Keys	40	40
Second function key	yes	no
Constant mode operation	yes	no

To assure you reliable performance, every calculator is subjected to severe environmental and reliability testing prior to release to production. In production, every one is thoroughly tested, then "burned-in", then thoroughly tested again. If there's any problem, we want to find it before it gets to you.

Inside, steel machine screws anchor all important structural elements—plastic welds and glue fastenings aren't good enough. A double-tough Mylar* barrier keeps dust and moisture from getting under the keyboard. The case is high-

strength, injection-molded plastic designed to take a beating. It's a quality calculator. And you know it as soon as you get your hands on one. The heft and solid feel tells you it's a fine-quality instrument even before you press a key.

The SR-50 and SR-51 are human engineered, too, for maximum comfort and efficiency. For a hand or a desktop. Keys have positive-action, tactile feedback. And the bright, wide-angle displays are easy to read at your desk or on the go. Slim. Compact. Light. In your briefcase or on your belt, you'll hardly notice just 8.3 ounces.

Technological leadership and quality craftsmanship are why Texas Instruments can offer so much value at such low prices: \$109.95 for the SR-50. \$179.95 for the SR-51.

20 Preprogrammed Conversions

FROM	TO
mils	microns
inches	centimeters
feet	meters
yards	meters
miles	kilometers
miles	nautical miles
acres	square feet
fluid ounces	cubic centimeters
fluid ounces	liters
gallons	liters
ounces	grams
pounds	kilograms
short ton	metric ton
BTU	calories, gram
degrees	gradients
degrees	radians
°Fahrenheit	°Celsius
deg. min. sec.	decimal degrees
polar	rectangular
voltage ratio	decibels

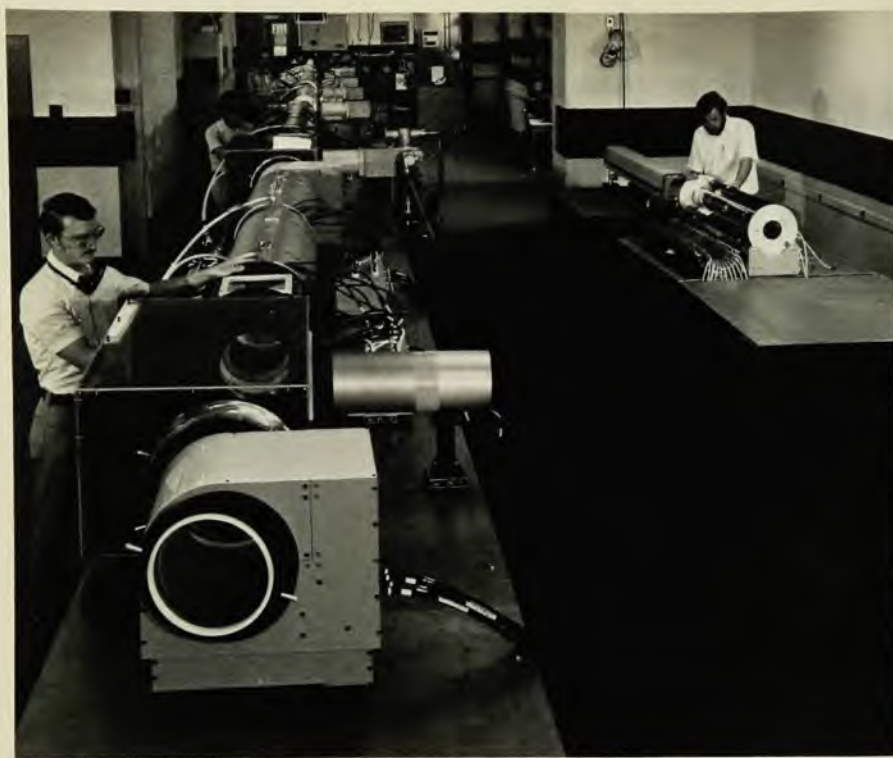
See them at your nearest TI calculator retailer. Or, send for our new fact-filled color brochure. It details the outstanding capability of both the SR-50 and SR-51 with full feature descriptions, sample problems, entry-method considerations and more. Circle the reader service number. Or write, Texas Instruments, M/S358, P.O. Box 22013, Dallas, Texas 75222



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This terawatt laser system, Cyclops, may be employed in the irradiation of x-ray laser targets at the Livermore laboratory. Cyclops, the world's most powerful single laser system, was developed in support of the laboratory's laser-fusion program. Figure 6

is shown under development, in figure 6.

Actually, it is rather difficult to achieve the brightness required for x-ray laser pumping with Nd-glass lasers, as the focal spot from existing high-power lasers of this type cannot be made much smaller than about 50 microns in diameter. From the point of view of focal-spot brightness, it would be desirable to have available a diffraction-limited laser in the visible or near ultraviolet, such as the high-power ruby laser being developed at the Los Alamos Scientific Laboratory by Robert Carman. Indeed, the pumping of lasers operating near $\lambda = 1 \text{ \AA}$ may require the development of ultrahigh-power, diffraction-limited ultraviolet lasers.

Applications

The most obvious experimental evidence for lasing is the presence of an intense collimated beam of monochromatic radiation directed along the fiber axis. Even for primitive x-ray lasers, the brightness of such a beam should be extremely high. In fact, x-ray fluences greater than about 10^3 J/cm^2 would be expected for a 1-keV device. This suggests an obvious—indeed, unavoidable—method of detection of true x-ray lasing action: One listens for a distinct report as a plasma plume jets out of the nearest surface irradiated by the laser's beam. The duration of the x-ray pulse has an upper-bound given by the length of the pumping wave pulse. For x-ray lasers pumped with presently available

high-power lasers, the pulse would not be longer than about 10^{-13} sec, the radiative lifetime of the upper state. The actual pulse duration might be much shorter than this, and could be as short as 10^{-16} sec, the reciprocal of the lasing linewidth.

The frequency coherence of the x-ray laser pulse will depend on the degree of line narrowing and other nonlinear effects in the medium, which might be significant if the gain is high enough. The spatial coherence of the laser beam will be determined by the number of transverse modes contributing to its output pulse. For an x-ray laser operating near threshold, the number of modes contributing will be quite high and the spatial coherence correspondingly poor. To produce spatially coherent beams, it will be necessary to develop x-ray lasers with very high gain and small angular divergence, so that only a few modes predominate. These lasers will therefore have to be relatively long ($l > 1 \text{ cm}$), which will necessitate the development of means for sweeping a traveling-wave pumping pulse over such lengths.

Since the first x-ray laser will probably not produce very coherent beams, their first applications are likely to exploit only the exceedingly high brightness and short duration of the output pulses. Such extremely short x-ray pulses could be used for flash radiography where changes on subpicosecond time scales are important; for example, one could study aspects of the structure

of shock waves in solids in uniquely high space and time resolution. Examination of dense plasmas, such as those expected to be produced in laser-induced fusion experiments,¹⁸ would also be greatly facilitated. The revolutionary advances in determining the structure of matter that we mentioned at the outset will follow as the pulse quality of x-ray lasers is refined by further work.

* * *

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