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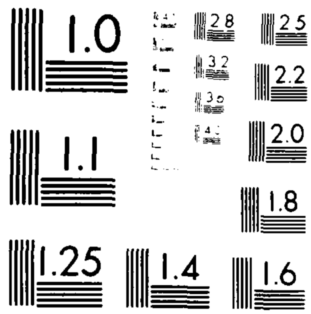

MICROCOPY RESOLUTION TEST CHART

CHAPTER 20

Potential Characteristics and Applications of X-ray Lasers

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20.1 INTRODUCTION

Coordinated movement is often found in Nature, for example ocean waves, or created by man, as in a parade. Coherent motions are at least fascinating and frequently useful. Such is certainly true for electromagnetic waves. Ordinary sources produce incoherent photon fields by spontaneous emission. Now it is well known that masers and lasers produce coherent, spatially and temporally coordinated electromagnetic waves due to stimulated emission. Lasers with outputs in the IR, visible, near-uv and vacuum-uv regions are available. Major efforts are being made to produce laser action in the extreme-uv and X-ray regions. Interest in X-ray lasers seems to be particularly keen[1]. Much of the motivation for research on X-ray lasers derives from their potential uses. Both radiation physics and materials studies would be stimulated by the availability of X-ray lasers, much as longer-wavelength lasers have produced a rich harvest of research results and new capabilities. However, rapid decay rates, high absorption cross-sections and the lack of good mirrors to form resonators in the soft X-ray region combine to necessitate extremely high pump powers. Also, many unwanted processes are activated by high-energy-density pumping so that low efficiencies are expected. In short, production of conditions favourable to laser action in the X-ray region with a net positive gain is difficult. Despite this, considerable progress toward an X-ray laser has been made in recent years.

This chapter is primarily a limited review of research on X-ray lasers and of the applications which may be possible when a source is available which emits short, monochromatic and intense pulses as coherent X-rays. Some of the progress toward producing short-wavelength coherent radiation, either by direct laser action or by frequency manipulation, is summarised in Section 20.2. Reports of X-ray laser action and spectroscopic evidence for relevant population inversions are discussed in Section 20.3. Potential X-ray laser characteristics, which are derived from the work to date and which will determine applications, are discussed in Section 20.4. Included is a comparison with two other bright X-ray sources, namely multi-million degree plasmas and GeV electron storage rings. Section 20.5 is concerned with the heating which will occur when an X-ray laser pulse strikes condensed matter. A simple calculational technique and some results are given there. Possible areas of X-ray laser usage are reviewed in Section 20.6. The final section discusses geometries which may be favourable for production of X-ray laser action, and multilayer reflectors which may make possible short-wavelength resonators. Brief attention is given at the end to other novel radiation sources, including potential γ-ray lasers.

This chapter is neither a comprehensive nor a critical review. Many schemes for X-ray lasers have been advanced and numerous theoretical treatments are available. These are largely ignored, with apologies to the authors, in favour of citing experimental articles which illustrate the current status and trends. Several published reviews of X-ray laser research are available[2-5]. Attention is invited especially to the comprehensive 1976 review by Waynant and Elton[6], which was updated recently[7,8]. Jorna and his colleagues have produced a wide-ranging, unpublished study of X-ray laser applications[9]. Bibliographies of work on X-ray laser research are also available[10,11].

20.2 COHERENT VACUUM-UV GENERATION

The ability to generate coherent electrical waves in conductors and, later, to transmit coherent electromagnetic waves is traced in Figure 20.1[3]. The peak frequency line is a classical 'growth curve' with a wide region of exponential variation. The first device based on stimulated emission, the ammonium maser, falls well below the curve. Interestingly, the ruby laser invented by Maiman in 1960 falls on a line near the points for devices developed much earlier. In almost 20 years since the first ruby laser (0.69μm), lasers have proliferated to cover almost all wavelengths in the 0.1-10 μm range. In fact, tuneable lasers are available over all of that range except for some regions below 0.2 μm[13-15].

The highest-frequency points in Figure 20.1 represent work done about 10 years ago by groups at the Naval Research and IBM (Yorktown Heights) Laboratories. Electron discharges were employed to cause lasing in the Lyman and Werner bands of molecular

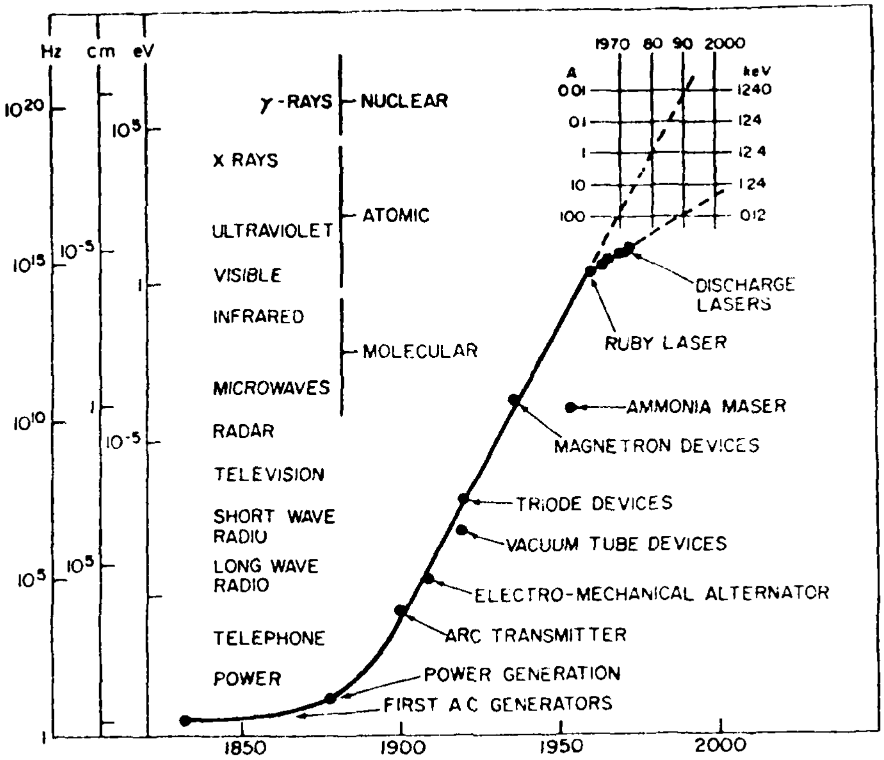

Fig. 20.1 History of the ability to generate coherent electric and electromagnetic waves, as updated[3] from a compilation by Eaglesfield[12].

hydrogen without the use of resonant cavities. The shortest wavelength achieved was 116.1 nm (10.7 eV), a transition in the Werner band[16,17], as shown in Figure 20.2. This represents the high-frequency record for verified direct lasing action.

High-power lasers have figured prominently in recent efforts to produce short-wavelength coherent radiation in two ways: (i) in frequency manipulation experiments, and (ii) as energy sources to pump plasma media for direct laser action. High-frequency coherent radiation has resulted from harmonic generation (frequency summation) experiments which exploited the non-linear properties of matter subjected to the intense electromagnetic fields of laser pulses. Metallic vapours, rare gases

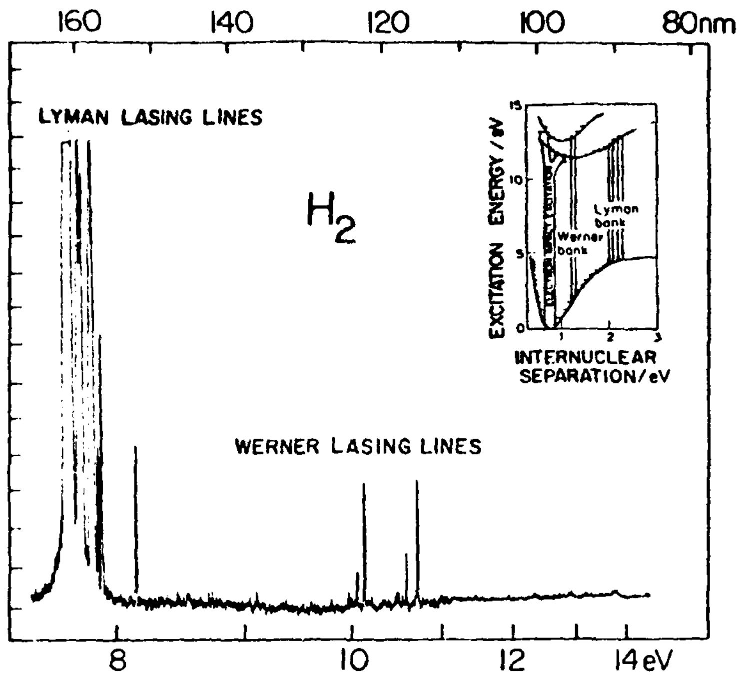

Fig. 20.2 Densitometer tracing of H_2 vacuum-uv laser output obtained by Waynant[16]. The insert shows the transitions in H_2 which produce the Lyman and Werner lines.

and molecular gases have been shown to have the combination of high-order susceptibility and low absorption necessary for non-linear interactions and phase matching over extended paths. Extensive theoretical and experimental work has been done on third and higher order susceptibilities and their enhancement due to resonances when an energy level of the non-linear medium is near some multiple of the driving laser frequency. The present record wavelength of 38.0 nm (32.6 eV) was achieved by generation of the seventh harmonic of quadrupled Nd radiation in He gas[18,19]. Figure 20.3 shows the spectrum of this short-wavelength coherent radiatio

The past two years have not seen any verified reports of direct laser action below 116.1 nm or frequency manipulation below 38 nm. Disputed or unchecked reports of laser action have been made and are mentioned in the next section after some introductory considerations.

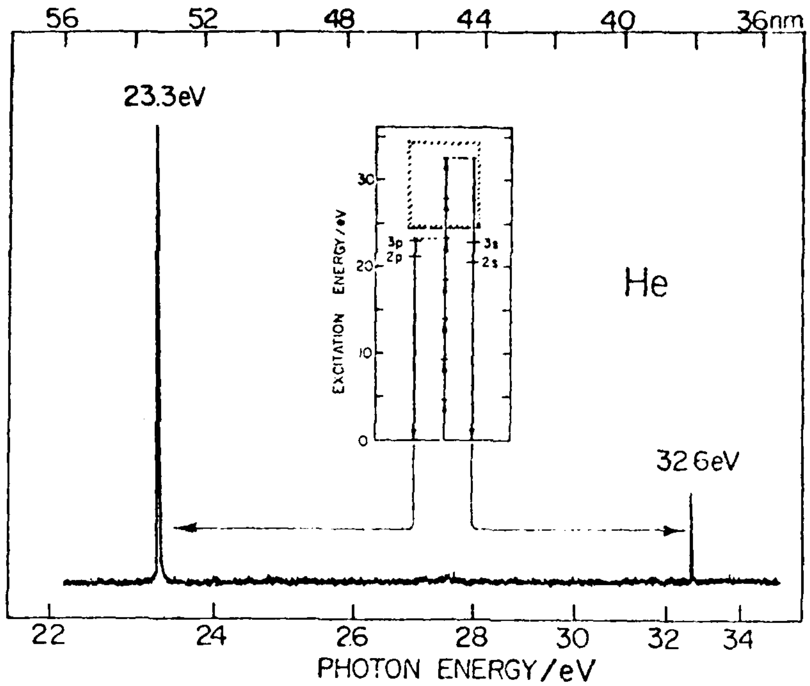

Fig. 20.3 Densitometer tracing of the spectrum of coherent radiation obtained by fifth and seventh order non-linear interactions in He excited by the fourth harmonic of a Nd laser and measured by Reintjes et al[18]. The insert shows the energy levels of helium.

20.3 RECENT X-RAY LASER RESEARCH

This section begins with a consideration of the mechanisms and pumps relevant to X-ray laser action. Reports of gain below 100 nm (12.4 eV) and spectroscopic evidence for high-energy population inversions are discussed in the rest of this section.

The possibility of an X-ray laser was discussed soon after the demonstration of the first laser in 1960. Most schemes for X-ray lasing now envisage a pulsed arrangement in which radiation from spontaneous decay is amplified by stimulated emission. Resonators may be used to photon energies up to ca. 100 eV, beyond which absorpti , heating and damage will restrict the use of mirrors. Amplification of a spontaneous (or input) intensity I_0 by a pumped medium of length L yields an intensity

$I = I_0 \exp(\alpha L)$ where the net gain per unit length α is the product of the peak stimulated emission cross-section σ_s and the inverted population N, less the propagation loss per unit length (due to photon absorption and scattering). That is $\alpha = \sigma_s N - \alpha_{loss}$. It is possible to have an inverted population without having positive gain ($\sigma_s N < \alpha_{loss}$), i.e., without laser action.

Many physical mechanisms have been considered as means of achieving X-ray laser action. In order to produce the required inverted population, it is necessary to either (a) depopulate a core level in the presence of filled, less-bound levels, or (b) to populate a normally vacant excited state above a state which is at least partially vacant. Photo-electron ejection or collisional ionisation of core levels is central to most schemes in the first group. In the second group of mechanisms, photo or collisional excitation, collisional or dielectronic recombination, and charge-exchange mechanisms have been suggested to populate normally vacant excited states. Resonant charge exchange is an attractive mechanism for the production of lasers above 100 eV because the very large cross-sections for this process relieve the density requirements for pumping[6]. Some proposed methods require two mechanisms to be operative.

Energy sources (pumps) are often the pacing element in the development of high-power and short-wavelength lasers[20]. For a soft X-ray laser near 100 eV, a pumping power density near 10^{12} W cm^{-3} is required[6]. This value is only for the inversion of interest, not including energy in other excitations. It increases as the fourth power of the X-ray laser photon energy. Such high pump power densities indicate that plasmas are the most likely media for X-ray laser action. Plasmas are problematic because most of their energy resides in unwanted modes such as particle kinetic energy, rather than in the inversion. Furthermore, dense plasmas tend to have short equilibrium times, i.e., an inverted population may be destroyed too quickly by collisions[21].

Photon, electron and ion beams, as well as electrical discharges, have all been considered as pumps for X-ray lasers. Ultraviolet and X-ray radiation from electron storage rings (synchrotron radiation) or from plasmas also have been suggested as energy sources. Of all the potential X-ray laser pumps, longer-wavelength (IR or visible) very high power lasers are most widely considered as pumps for a plasma X-ray laser medium. Such lasers can produce power densities in excess of 10^{18} W cm^{-3}, but the heated volume is small ($10^{-3} cm^3$). Electron beams and discharges can yield plasma power densities greater than $\sim 10^{14}$ W cm^{-3}. Electron-beam heated plasmas are relatively cold (~10 eV) for X-ray laser production, but discharge heating can yield temperatures approaching 10 keV. Pulsed ion beams which are now available produce values above 10^{14} W cm^{-3}, but ion-heated plasmas are too cold (~10 eV) to be used as X-ray laser media. Steady ion beams and synchrotron radiation sources tend to be deficient in available power. X-UV radiation is emitted from plasmas with high power but it is not easily focussed into a small X-ray laser medium. Two-step pumping schemes have been suggested in order to simultaneously achieve the proper set of temperature and density conditions for the production and adequate maintenance of a population inversion. The use of travelling-wave pumping is attractive because it would lower the pump energy requirements. In this scheme, only part of the X-ray laser medium is excited at any one instant, and the pumped region is swept along synchrotronously with the X-ray pulse.

A matrix of physical mechanisms and energy sources could be constructed to categorise approaches to producing an X-ray laser. It would show that the same energy source (e.g. lasers) has been envisaged for the production of an inverted population by a variety of mechanisms, and conversely, the same mechanism (e.g. collisional excitation) might be employed with different pumps. Waynant and Elton have estimated the particle densities necessary to achieve laser action in the region from ca. 10 eV-10 keV for various mechanisms and pumps in plasmas and ion beams[6]. A simplified plot, limited to plasma media[22], is given in Figure 20.4. It shows that resonant

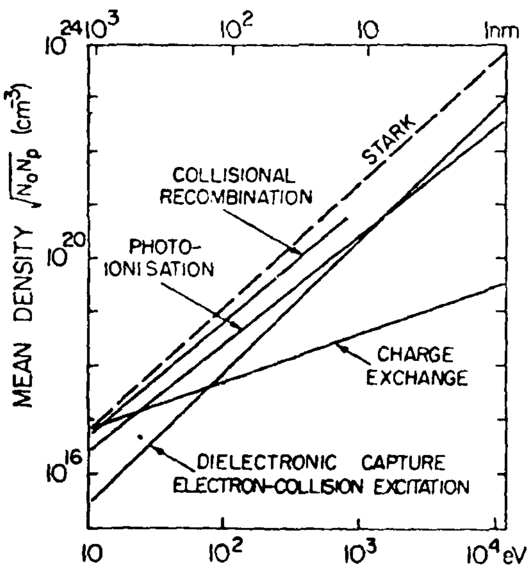

Fig. 20.4 Mean desnity of ground-state (N_0) and pump (N_p) particles necessary for laser action with a gain coefficient of five calculated as a function of laser output photon energy for various mechanisms by Elton and his colleagues[6,22]. Stark broadening sets a limit (dashed line) on useful densities.

charge exchange requires the least density of pumped (N_0) and pumping (N_p) particles for lasing above 100 eV. Other mechanisms are within about one order of magnitude of each other over the entire VUV to hard X-ray range.

In order to assess the success of X-ray laser experiments, it is necessary to apply to their results criteria for the observation of positive gain[6,21]. Some criteria for lasing at longer wavelengths are related to the unique characteristics of laser output, such as coherence, monochromaticity (line-narrowing), collimation and power level. These characteristics are not expected to be very useful for tests of early X-ray lasers. Coherence and line-narrowing are relatively difficult to measure adequately in the X-ray region. The collimation and output power of a laser medium can be determined. However, such measurements must be done with sufficient spectral, spatial and temporal resolution to distinguish the laser line from other radiation emitted by the lasing medium. Because a linear plasma may be the most likely geometry and medium for an early X-ray laser, tests of output dependence on length ($\sim \exp[\alpha L]$) and on direction (along and normal to the plasma) are expected to be useful to determine X-ray laser action. It is also possible to employ spectroscopy of the relevant levels to determine a population inversion, even if the transition of interest is not observed directly.

Three reports of gain (direct laser action) at energies above 10 eV will next be reviewed in chronological order, along with the work which has contested each of the reports. Then a recent, unchecked experiment which yielded evidence of laser action near 200 eV will be discussed.

Jaeglé and his colleagues made thorough experimental and theoretical studies of X-UV spectra from laser-heated aluminium in a programme at Orsay which spanned more than a decade. The early work was concerned with the characteristics of the plasma emission[23]. Then two-plasma absorption studies in 1970[24] suggested the occurrence of laser action at 105.6 eV (11.74 nm) in 1971[25]. A mechanism involving auto-ionising transitions in Ne-like Al was invoked[26], and a gain coefficient near 10 cm^{-1} was reported[27]. Intensity anomalies, spectral line-narrowing and temporal narrowing were all observed in this work. The interpretation of their findings as gain by Jaeglé and co-workers was challenged by Valero[28] and Silfvast et al.[29] who ascribed the observations to self-absorption effects in non-uniform plasmas. Valero's work was rebutted by the French workers[30]. McGuire[31] hypothesised that X-ray coupling between the two plasmas and Auger transitions produced the observations. The X-ray laser research at Orsay has been reviewed by Jaeglé[32]. Additional experiments with elements near aluminium would probably be valuable in resolving the remaining disagreements on the interpretation of the effects observed in Aℓ plasmas. Whatever the ultimate outcome, the French work has produced and stimulated many valuable results in atomic and plasma physics. It is expected that the two-plasma technique will be used often in the future to measure opacities of highly ionised matter.

Kepros, Eyring and Cagle reported in 1972[33] the emission of coherent hard X-rays (~8 keV) from laser-heated gelatin containing $CuSO_4$. That report stimulated intense activity which lasted about two years. Both positive and negative results were reported in experiments which attempted to reproduce the results obtained on X-ray film in Utah. The detailed reports are reviewed elsewhere[6]. In the end, the failure of experiments with active detectors as well as theoretical arguments[34] have left scepticism about the original interpretation.

Zherikhin et al. published experimental evidence in 1977[35] for lasing at 211.1 eV (5.873 nm) in Na-like Cl with a gain of 10 cm^{-1}. Double-pulse heating of KCl crystals with a Nd laser was employed at the Spectroscopy Institute in Moscow. Elton and Dixon[36] ascribed the emission of interest to Li-like Na, and found no intensity anomaly when spectra taken axially and transversely to the elongated plasma of Zherikhin et al. were compared.

Ilyukhin et al. reported in 1977[37] on the observation of intense spots on film along the direction of a resonator axis. Radiation near 200 eV which produced the spots may be due to lasing of 3s-3p transitions in Ne-like Ca ions. Nd laser pulses containing 30 J in 2.5-5 ns were focussed to spots 0.4-0.8 mm wide and 10-40 mm long. These experiments (carried out at the Lebedev Physics Institute in Moscow) deserve verification at other laboratories.

In addition to the three reports of gain (Orsay, Utah, Moscow) and the recent resonator measurement with calcium ions (Moscow), there have been several experimental studies in which population inversions were observed. Quantitative spectroscopic studies, which formed the basis for the reports of population inversions, are discussed in the remainder of this section. Work done with carbon and neighbouring atoms is reviewed first. Then studies of aluminium and magnesium are noted.

Irons and Peacock made the first spectral measurements of an inverted population relevant to lasing above 10 eV[38]. Their 1974 paper reported the inversion densities of H-like carbon ions from a $(CH)_n$ target heated with a Nd laser. The results are shown in Figure 20.5. Inversions exist for 2-3, 2-4 and 3-4 principal levels. Gains near 10^{-5} cm^{-1} were computed. These values are too small for the direct observation of gain.

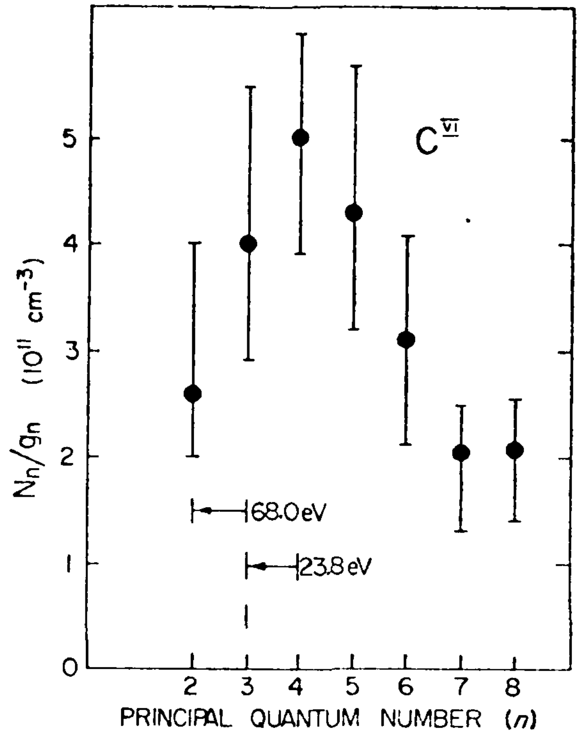

Fig. 20.5 Level population densities obtained by Irons and Peacock[3] from space-resolved spectra 2.8 mm from a laser-heated carbon target. Photon energies between inverted levels are indicated.

Dewhurst et al. also found an inverted population in the 2-3 Balmer line of H-like carbon in laser-produced plasmas[39]. Their experimental results were compared with a computer model which was employed to compute gain as a function of time. A peak gain of 0.02 cm^{-1} resulted. Recombination during plasma expansion into the vacuum reportedly provided the inversion in this work.

Dixon and Elton obtained the first spectroscopic evidence of intensity inversion in the 3-4 levels of H- and He-like carbon[40]. Their data are shown in Figure 20.6. In a second study, they observed an intensity inversion in the first (2-3) and second (2-4) Balmer series lines in H-like carbon[41]. The inversions were attributed to charge exchange which occurred when ions from laser-heated plasmas expanded into a low-pressure (1-10 Torr) buffer gas in the target chamber. Electron-ion recombination was not sufficient to account for the observed intensity inversions. In a recent

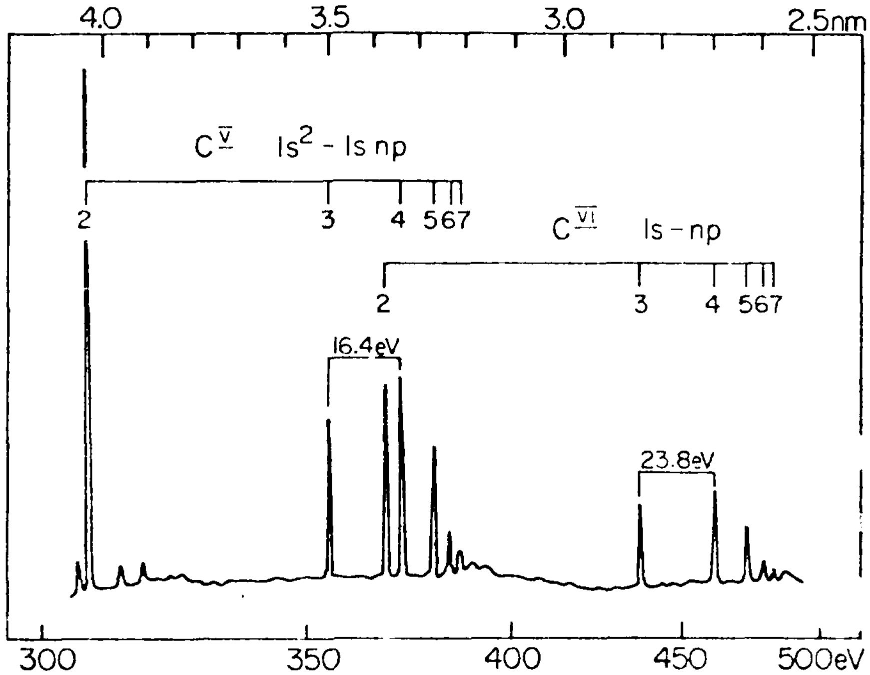

Fig. 20.6 Densitometer trace of the spectrum obtained 16 mm from a laser-heated carbon target with background gas of a few Torr pressure by Dixon and Elton[40]. The energy separation of lines from inverted levels is indicated.

experiment, the same authors and their colleagues again employed space-resolved grazing-incidence spectroscopy for other ion species, namely Li, B and N[42]. Differences in which the Rydberg level was populated in the various ions strongly support resonant-charge exchange as the mechanisms responsible for producing the inversions.

Several studies have involved aluminium or magnesium ions. Kononov et al. used laser heating and observed population inversions in the 3-4 and 3-5 levels of Li-like Aℓ[43]. A gain of 0.1 cm^{-1} for the 3d-4f line at 80.5 eV (15.4 nm) was inferred. Bhagavatula and Yaakobi obtained a 3-4 inversion in laser-heated He-like Aℓ ions which were allowed to expand near a cold piece of magnesium[44]. The authors attributed the inversion to recombination, while Eltron et al.[42] suggest that it may also be associated with resonant-charge exchange from Ne-like donor ions. In other work, Bhagavatula employed composite targets of magnesium and carbon to obtain 3-4 inversions in H- and He-like Mg ions[45]. The observed inversions were ascribed to resonant photo-excitation.

The experimental work reviewed in this section, and also theoretical estimates, form the basis from which to discuss the output characteristics of potential X-ray lasers.

20.4 ANTICIPATED X-RAY LASER CHARACTERISTICS

The output of X-ray lasers is expected to be unique and, hence, useful for new areas of research. X-ray laser applications, to be considered in a later section, will depend on the characteristics of the radiation field of such a source. In this section, we briefly review the primary quantities which are employed to describe an X-ray source and its emission. Then the qualities of a potential X-ray laser beam are discussed, based on the literature and some simple estimates. Because some of the uses of X-ray lasers are, or will be, pursued with alternative bright X-ray sources, this section also contains a brief discussion of X-ray fields from high-temperature plasmas and electron-storage rings.

Several quantities must be specified in order to describe a photon source and its radiation field. They include the source of energy, the relevant emission mechanisms, and the spectral (shape and intensity), spatial (beam cross-section and divergence) and temporal (pulse and repetition rate) aspects of the source, as well as spatial and temporal coherence and polarisation of the radiation. Brightness (energy/time/area/steradian) can be derived from the other source characteristics.

The characteristics of pulses from an X-ray laser are necessarily conjectural. Even if a proven X-ray laser existed now, it would be likely that others with different output parameters would be developed. Not withstanding these factors, there has been some discussion of potential beam characteristics from X-ray lasers. Andrews[46], a group at Lawrence Livermore Laboratory[34,47], Jorna et al.[9] and Fiton and Dixon[22] provide data on potential X-ray laser characteristics. Attention has centred on the 0.1-1 keV region, and we will assume X-ray laser output in this range.

The pump power and particle densities required for lasing action above 100 eV can be estimated from the basic equations for gain[6,22]. Comparison of energy-density values obtained from such calculations with the energy per atom in plasmas, which can be estimated simply from a coronal model[48], shows that X-ray lasant media are most likely to be in the plasma state. Plasma temperatures near or above 100 eV are needed to produce the ionisation and excitation corresponding to lasing in the

0.1-1 keV range. Medium atomic number plasmas are indicated because the lightest elements have only weakly bound levels and in heavy elements excitation tends to be spread across too many ionisation stages and excitation levels for efficient gain.

The geometry and divergence of an X-ray laser can be anticipated. The diameter d of the laser medium is expected to be near the diffraction limit, i.e. $d^2 > \lambda l$, where the wavelength λ is emitted from a lasant of length l[47]. The small d, and also a small value for l, are desirable to reduce the pump power requirements. But λl must be large enough to overcome losses, and values of l in the range of 1 mm to 1 cm are anticipated[9,46]. Hence for λ in the 1-10 nm range, d is of the order of 1-10 μm. The diameter and length values imply a divergence of the order of 10^{-3} or less. Clearly, making an X-ray laser of a few μm diameter as long as 1 cm is a challenge. It is possible to use single or multiple laser foci to achieve the required geometry but intense particle beams cannot be focussed to dimensions of the order of 1 μm.

The spectrum of an X-ray laser would consist of one or more intense lines in the 100 eV-1 keV range above a spontaneous-emission background in and beyond that spectral region. The amount of energy in the primary line has been estimated. Wood et al. give theoretical output energy densities, e.g. 10^3 J cm^{-2} at 100 eV and 10^4 J cm^{-2} at 1 keV[47]. Lasant diameters of a few μm then imply outputs near 10^{-4} J (10^{13} photons) at 100 eV and 10^{-3}J (10^{13} photons) at 1 keV. X-ray laser pulses of such energies can be compared with projected X-ray laser efficiencies and expected pump energies. Figure 20.7, due to Rhodes and Hoff[49], contains experimental laser efficiencies and a wide band of projected values. Variations in laser pumps, media, excitation mechanisms, population inversions and gain make such projections highly uncertain. Nonetheless, the estimated X-ray laser output at 100 eV (10^{-4} J) and at 1 keV (10^{-3} J) can be used with the projected laser efficiencies given in Figure 20.7 at 100 eV (10^{-4}-10^{-7}) and at 1 keV (10^{-5}-10^{-9}) to predict required pump energies. This indicates that pump energies of 1-10^3 J are needed for a 100 eV laser and 10^2-10^5 J for a 1 keV laser. Presently available lasers, and also electron and ion sources, have beam energies over 10^4 J. That is, projected X-ray laser output energies and efficiencies have significant overlap with available pump energies, although the estimates are extremely uncertain.

The temporal characteristics (pulse length and repetition rate) of an X-ray laser can also be discussed. The output pulse of a laser can be compared to the spontaneous emission lifetime, which is roughly 10^{-13} λ^2 (nm) in the soft X-ray region[34]. That is, the spontaneous lifetime is ca. 10 ps at 100 eV and 100 fs at 1 keV. The upper limit on the pulse length from an X-ray laser is determined by

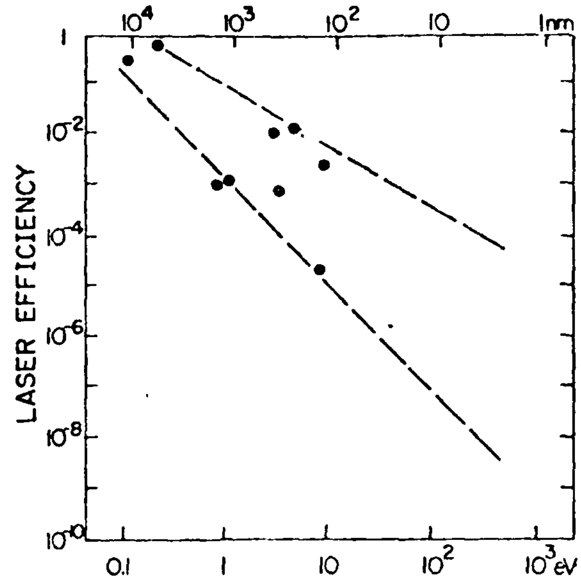

Fig. 20.7 Measured laser efficiencies as a function of laser photon energy plotted by Rhodes and Hoff[20]. The dashed lines indicate a wide region of projected efficiences for higher-energy lasers.

the active mechanism, the lasant medium and the duration over which the required high pump power can be sustained. Lasers with output pulses longer than the spontaneous lifetime are referred to as continuous-wave (cw) lasers. A lower limit on the pulse length can be estimated by reference to Figure 20.8. Pulse lengths for pulses containing 10-10^3 cycles of the electromagnetic field are given as a function of photon energy. The data point for an already-produced laser[50] shows that a similar laser pulse would be of the order of 10 fs at 100 eV and 1 fs at 1 keV. Realistically, in the absence of mode-locking and good resonators in the soft X-ray region, an X-ray laser could be expected to have a pulse length approaching 10 ps for 100 eV and 100 fs for 1 keV. These values, which are equal to the spontaneous emission lifetimes, may be lower limits. They are influenced by the pulse lengths of energetic lasers which could be used as pumps. Laser pumps which have outputs near 10^3 J now have pulse lengths near 1 ns, while particle beam pulses with comparable energies are 10-100 times longer. Shorter pulses are available from lasers with energies near 10 J, e.g. 10 ps. Hence, steady-state (cw) operation of

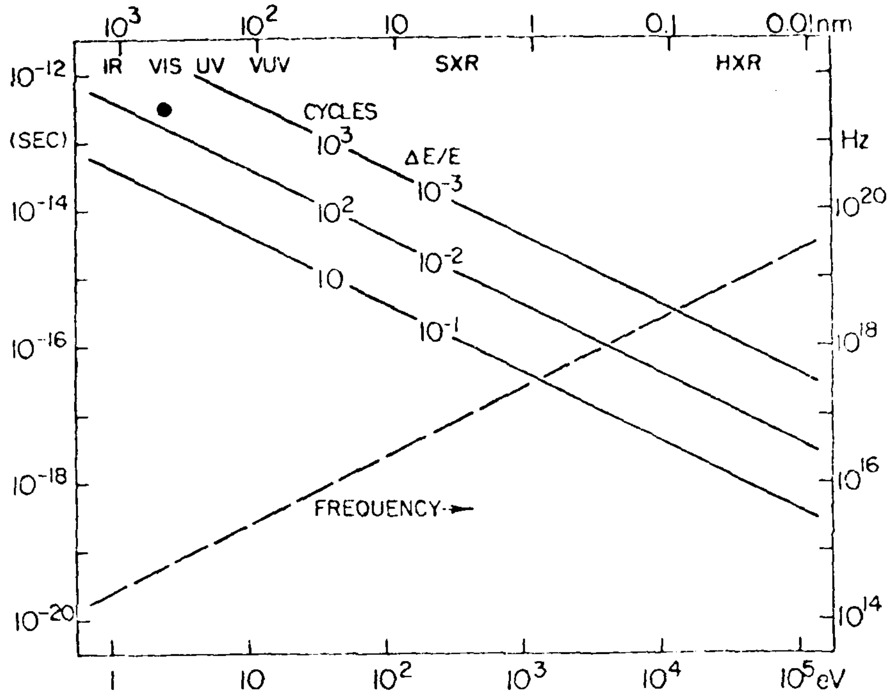

Fig. 20.8 Plot of laser pulse length vs. laser photon energy as a function of the number of cycles in the laser pulse and the relative line width ΔE/E from the Uncertainty Principle. The dot indicates the sub-ps pulse length already demonstrated with a Nd laser[50]. The relationship between electromagnetic frequency and photon energy is also given (dashed line).

X-ray lasers is likely for the near-term, even using lasers as pumps, since sufficiently energetic pump pulses are generally longer than the spontaneous lifetimes in the 100 eV-1 keV range. The repetition rate of an X-ray laser can be expected to be low because the needed high-power pumps cannot be fired with high frequency. Lasers which have enough energy to be candidate pumps generally require about 10^3-10^4 s between shots, while high-power electron and ion sources require about 10^4 s between shots.

Lower limits on the spectral width of X-ray laser lines can be estimated from Figure 20.8, which gives the Uncertainty Principle values for relative line-widths. At 100 eV, 10 ps pulse lengths imply minimum ΔE/E values of 10^{-5} and ΔE of at least 0.001 eV. At 1 keV, 100 fs pulse widths give ΔE/E of 10^{-4} or greater and ΔE above 0.1 eV. That is, X-ray laser line-widths could be smaller than comparable energy lines emitted by plasma sources in which there is significant Stark (pressure) or Doppler broadening, although they are ultimately limited by the Uncertainty Principle.

The coherence and polarisation of X-ray laser beams remain to be discussed. The coherence of an X-ray laser is not expected to approach that of existing longer-wavelength lasers because of the expected poor performance or lack of resonators. There is only one prediction of spatial coherence (which is related to the number of transverse modes), namely that of Jorna et al.[9] who expected $\lesssim 10^3$ wavelengths for the coherence length. No specific predictions have been made for temporal coherence (which depends on the line-narrowing resulting from gain). A laser medium without a resonator is not expected to produce polarised radiation.

It is worth emphasising that quite different X-ray beams could be produced if suitable resonators can be found for photon energies above 100 eV. Reduced pumping requirements, shorter pulses, improved coherence and possibly polarisation would result from the use of a resonator. Prospects for resonators at high photon energies are discussed in the final section.

Two intense sources of X-ray already exist and can be compared with the output expected from X-ray lasers, viz. high-temperature plasmas and storage rings. The nature and characteristics of each of these are summarised briefly in the remainder of this section.

Plasmas, heated by photons (lasers) or electrons, emit intense X-rays if their temperature exceeds 10^6 K[51]. Laser-heated plasmas are relatively controllable and clean (debris-free) compared to electron-heated plasmas. Here we consider the characteristics of X-rays from a plasma produced by 10^3 J, ~1 ns pulses from a Nd laser (1.06 μm)[52]. The incoherent and unpolarised radiation consists of both lines and continua. As much as 30% of the incident energy can be radiated above 0.1 keV from a volume of about 10^{-3} mm^3 into 2π sr in a 1 ns pulse every 10^3 s.

Synchrotron radiation in the X-ray region is emitted when relativistic (~ 1 GeV) electrons orbit in a magnetic field within an evacuated storage ring (radius = 1-100 m)[53,54]. The electrons, which are bunched, emit intense, smooth continuum radiation each time they orbit the ring. The source size is typically about 0.2 × 2 mm in cross-section, with radiation emitted into ~1 mrad normal to the ring around its entire circumference. Pulse lengths are in the 0.1-1 ns range, with repetition intervals generally between 10 and 10^3 ns. The incoherent radiation is polarised ($\bar{E}$ in the plane of the ring). Many calculations of synchrotron radiation intensity are available but there are few data on the absolute intensity emitted by orbiting electrons.

Comparisons of X-ray sources are complicated by the geometrical and spectral differences. We note especially that X-ray lasers will have dominant line emission above weak background emission. Hence, monochromators will not always be needed for experiments. Although plasma sources emit strong lines, it is usually necessary to use monochromators with them. The continuous spectrum of synchrotron radiation almost always requires monochromatisation before use. If broad-band radiation can be used, for example, in radiation-damage experiments, then plasmas and storage-rings compare more favourably with potential X-ray lasers.

Despite the difficulties in comparing sources, the following compilation of X-ray characteristics for the 0.1-1 keV region has been made:

TABLE 20.1

	X-Ray laser [a]	Laser plasma [b]	Storage ring [c]
Source size/mm	0.01×0.01	0.1×0.1	0.2×2
Emission angle/sr	$(10^{-3})^2$	2π	$10^{-3} \times 2\pi$
Emission time/s	10^{-12}	10^{-9}	10^{-9}
Interpulse time/s	10^{3}	10^{3}	10^{-6}
Photons/pulse^{-1}sr [d]	10^{19}	10^{15}	10^{13}

a X-Ray laser characteristics described above.

b 10^3J, 1 ns Nd laser, 30% conversion to X-rays.

c GeV storage ring with 0.1 A current.

d 1% band-width ($\Delta E/E$) for plasma and storage ring.

The considerable brightness of a potential X-ray laser is noteworthy. It is due, in very general terms, to the short pulse and collimation expected for X-ray laser pulses. Laser-heated plasmas have longer pulses and much greater emission solid angles but they emit a relatively large energy in X-rays. When significant thermonuclear burn is achieved in laser-heated plasmas, much greater X-ray intensities will be available from that type of source. Storage rings, although bright X-ray sources compared to X-ray tubes[55,56], have a much lower brightness in a single pulse than present laser-heated plasmas. They run continuously however, and can yield X-rays harder than 10 keV, an energy where laser plasmas have little relativity emission and where X-ray lasers may be extremely difficult to produce. Virtually all laboratory sources of X-rays, from radioactive materials and X-ray tubes, through storage rings, to plasmas and eventually X-ray lasers, have unique and useful characteristics.

20.5 X-RAY HEATING OF MATTER

X-ray absorption will increase the temperature of the absorber. X-ray detectors based on thermal effects are in common use for plasma diagnostics. High values of X-ray irradiance can lead to melting. Mallozzi et al. showed that X-rays from laser-heated plasmas were sufficiently intense to melt a thin layer of lead[57]. Clearly, higher X-ray irradiances will lead to vaporisation and ionisation of a solid absorber. The output characteristics of a projected X-ray laser, given in the last section, can be used to compute the high irradiance values which might be available. Taking the divergence into account gives 3×10^{8} to 3×10^{10} W cm^{-2} for 10^{-4}J at 100 eV (10 ps) and 3×10^{11} to 3×10^{13} W cm^{-2} for 10^{-3}J at 1 keV (100 fs) for distances of 10-100 cm from a hypothetical X-ray laser. What temperatures would be produced by such X-ray irradiances?

The heating of matter due to the absorption of X-rays near 0.1-1 keV is *qualitatively* different from heating by laser photons at the longer wavelengths. Radiation from current lasers penetrates the target plasma it forms until it reaches the critical density (n_c). At that point, the laser and plasma frequencies are equal, and at higher densities (greater plasma frequencies) the plasma is opaque to the laser radiation. Significant absorption of laser light, as well as some reflection and tunnelling, takes place in a region near the critical density which can be as thin as about 1 μm. For CO_2 lasers (10.6 μm) $n_c \sim 10^{19}$ electrons cm^{-3} and for Nd lasers (1.06 μm) $n_c \sim 10^{21}$ electrons cm^{-3}. A laser operating at 100 nm would have $n_c \sim 10^{23}$, a value near the electron density in ordinary solids. Hence for a laser operating at 100 eV (~ 10 nm) or 1 keV (~1 nm), there will be no critical density (in the absence of extreme compression!) and ordinary absorption will prevail. That is, near a laser wavelength of 100 nm (10 eV), plasma absorption of photon radiation changes from a classical, cooperative (many-body) effect to a quantum, single-electron effect.

The heating of matter by X-rays can be computed in two steps assuming that it is rapid compared to conductive cooling times. First, the energy (eV) per atom produced by the absorption of X-rays is calculated, as described in the next paragraph. Then, relationships between eV atom^{-1} and temperature, as obtained from thermodynamics or plasma models, are employed to estimate the state (hot solid, liquid, vapour or plasma) attained for particular conditions (W cm^{-2} of a given X-ray energy incident on a specified solid). Such estimates are given later in this section and compared to heating by other photon (laser) and particle beams.

The heating (eV $atom^{-1}$) of solids by X-rays is easily estimated for a given incident energy density (J cm^{-2}) using 6×10^{18} to convert joules to electron volts:

$$\frac{eV}{atom} = \frac{6 \times 10^{18}}{6 \times 10^{22}} \frac{J(abs)}{cm^3} = 10^{-4} \frac{J(abs)}{cm^3} = 10^{-4} \left(\frac{J}{cm^2}\right) \mu .$$

A typical atomic volume of $(2.5 \text{ Å})^3$ or 6×10^{22} atom cm^{-3} was used in order to obtain a generally useful formula. The linear absorption coefficient μ usually falls in the 10^2-10^5 cm^{-1} range for 100 eV-1 keV photons. The J cm^{-2} values are computed from 10^6 J/R^2 for a laser with 10^{-3} divergence which emits J joules, where the target is R(cm) from the X-ray laser. Figure 20.9 is a plot of the above equation for R = 10 cm. The eV $atom^{-1}$ values range from that corresponding to room temperature (300 K = 0.026 eV) to values over 10 eV $atom^{-1}$ which are consistent with ionisation (plasma formation).

The eV $atom^{-1}$ value necessary to achieve a specified temperature for any state of matter is readily computed. Tabulated values of specific heats, and latent heats or fusion and vaporisation, can be used for solid, liquid and vapour states. In the plasma state, ionisation as well as kinetic energies have to be taken into account. This is easily done for equilibrium models, such as the coronal model in which collisional ionisation is balanced by radiative recombination[48]. The eV $atom^{-1}$ value computed from the coronal model is shown for a few elements in Figure 20.10. The shell structure of atoms causes undulations in the curves of eV $atom^{-1}$ vs. temperature. Values of 10 eV $atom^{-1}$ correspond to temperatures near 1 eV (10^4 K).

To illustrate the calculation of X-ray laser heating using Figures 20.9 and 20.10, consider a 10^{-4} J pulse of 100 eV radiation incident on Aℓ. The linear absorption coefficient μ is near 10^5 cm^{-1} which gives 10 eV $atom^{-1}$ at 10 cm and 0.1 eV $atom^{-1}$ at 100 cm from Figure 20.9. The 10 cm value indicates a plasma temperature slightly over 1 eV from Figure 20.10. The first ionisation potential of Aℓ is 6.0 eV and the average ionisation stage at 1 eV temperature is 1.0 electrons removed. Hence, use of the ground-state value for μ is acceptable because the value of μ is determined by L-electron absorption at 100 eV and the L-shell is not ionised at 1 eV. The 100 cm value of absorbed energy is not enough to melt aluminium. It corresponds to heating from 300 K (room temperature) to 640 K. For 10^{-3} J at 1 keV (where

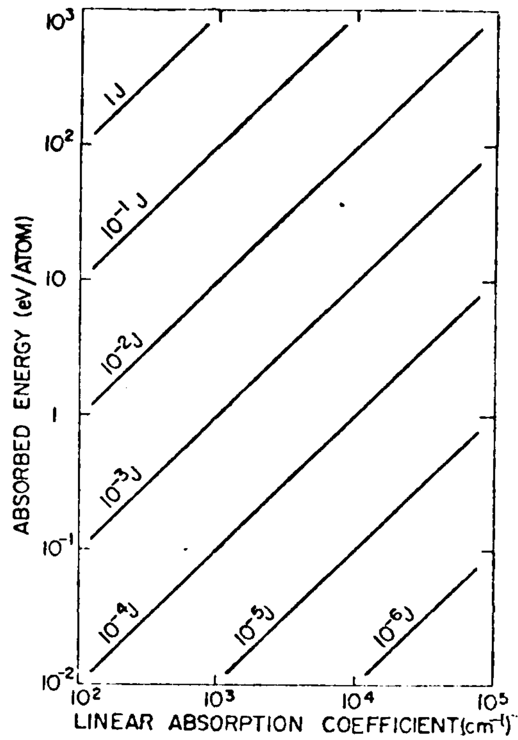

Fig. 20.9 Energy absorbed per atom by a target 10 cm from an X-ray laser, as a function of the linear absorption coefficient, for the given energy outputs by a hypothetical X-ray laser having a 10^{-3} rad divergence. A nominal interatomic spacing of 2.5 Å was assumed in order to obtain this universal plot.

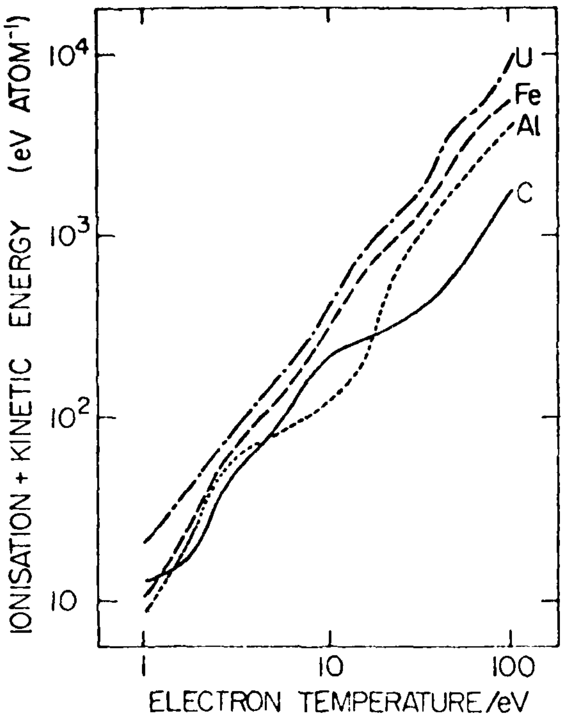

Fig. 20.10 The total (ionisation and kinetic) energy per atom as a function of electron temperature computed from the coronal plasma model of Mosher[48] for four elements.

$\mu = 3.2 \times 10^3$ cm^{-1} for Aℓ), Figure 20.9 shows that the surface atoms would absorb about 1 eV $atom^{-1}$ at 10 cm from the X-ray laser. This is enough to melt but not vaporise aluminium. At 100 cm, absorption of 10^{-3} J of 1 keV radiation would produce only a small temperature rise (3 K) in aluminium.

The heating of matter by X-ray laser photons can be compared to that produced by longer-wavelength lasers, and by electron and ion beams. Figure 20.11 shows plasma temperatures achieved as a function of irradiance for various quanta[58]. CO_2 and Nd laser beams are stopped in narrow regions near the critical density. Hence, they heat relatively small amounts of matter and produce high temperatures. The lower critical density of CO_2 compared to Nd means that the absorbed energy must be carried

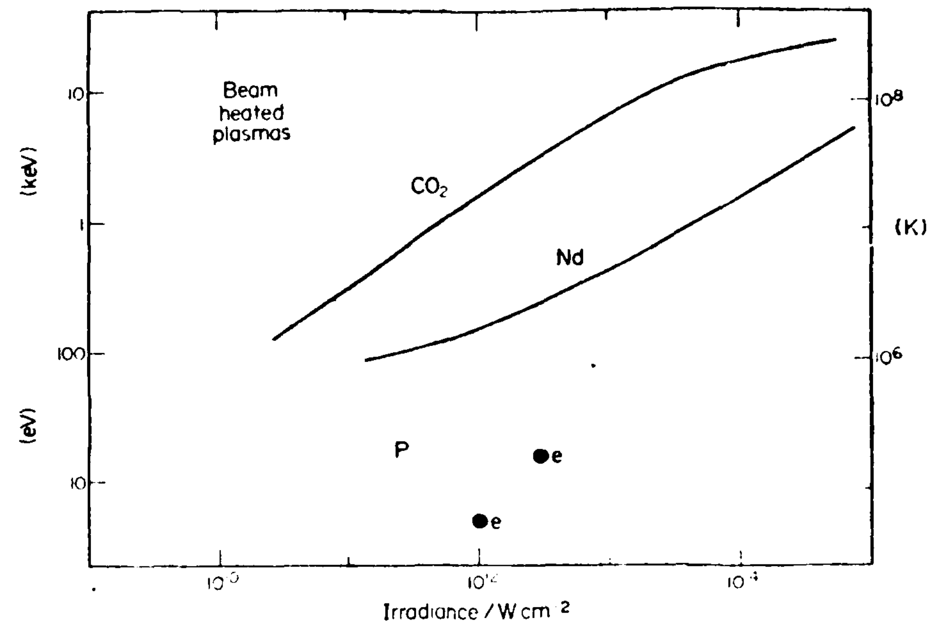

Fig. 20.11 Measured plasma temperatures for the heating of solid targets by CO_2 and Nd lasers, proton beams and electron beams as a function of irradiance[58]. The energetic (~ MeV) particle beams are more penetrating than laser pulses so that they heat more matter and yield lower temperatures.

by fewer particles, so higher temperatures are produced by the CO_2 wavelength. High particle irradiances can be achieved only for rather high energies (~MeV). These result in penetration depths in solids of the order of 10 μm for protons and 1 mm for electrons. Hence, electrons heat the most matter and produce the lowest temperatures as shown in Figure 20.11. In the last paragraph, a plasma temperature of 1 eV was computed for Aℓ 10 cm from a 10^{-4} J, 100 eV laser. This corresponds to about 1 J cm^{-2} or 10^{11} W cm^{-2} for a 10 ps pulse. This value shows that an X-ray laser of the projected output near 1 mJ would not be useful for the production of high-temperature plasmas. Although the absorption length is small for 100 eV photons in Aℓ (~30 nm), the energy is deposited at high (solid-state) density, so many atoms are heated compared to long-wavelength laser absorption which takes place at much lower densities.

Even though heating by X-ray laser pulses is weak compared to existing CO_2 and Nd lasers, the effects of an X-ray laser pulse on a sample are drastic compared to irradiation by ordinary X-ray sources. Temperature rise times of 10^{12}-10^{16} K s^{-1} can be expected. If plasma, vapour or even melted material is ejected from a target surface, a shock wave will propagate into (and heat) the target. Rapid expansion, even in the absence of melting, would also produce a pressure wave. The possibility of the fast heating of targets (samples) highlights the potential uses of X-ray lasers.

20.6 SPECULATION ON X-RAY LASER APPLICATIONS

The possibility of performing new studies, which might capitalise on the unique qualities of radiation from an X-ray laser, has been a major driving force for research in this area. It should also be possible to perform current experiments with improved intensities and resolutions. Lists of potential applications of X-ray lasers may be constructed from a review of the present uses of pulsed soft X-ray sources and their dependence on greater brightness[59,60], by an examination of the uses of current long-wavelength lasers with reference to their extension into the X-ray region[61] and from a study of the X-ray laser literature[6,9,[illegible]]. Clearly, some major applications in these areas, such as long-range communication along optical fibres, will not be possible with an X-ray laser. Nevertheless, many uses relate to laser brightness or wavelength.

Two useful compilations of potential X-ray laser uses are available. Waynant and Elton[6] have classified many applications according to the characteristics of an X-ray laser pulse, e.g. monochromaticity. In this case, the emphasis lies in the area of exploiting unique X-ray beam characteristics. Jorna et al.[9] have grouped and examined X-ray laser uses according to their field of study, e.g., metallurgy, and experimental technique, e.g., electron spectroscopy. Such an approach tends to emphasise the ability to undertake new experiments, as well as improving existing techniques. In this section, potential X-ray laser uses have been grouped into four categories: (i) X-ray laser research; (ii) radiation physics; (iii) materials analysis; and (iv) materials modification. These categories, whilst broad and overlapping, are suggested by present laser usage. Although they are not all-inclusive, the categories provide a simple framework for the classification of possible X-ray laser applications. Areas in which X-ray lasers are not likely to be useful, despite contrary predictions, are also mentioned at the end of the section.

X-ray laser developmental research is the first major application area. Lasers operating at longer wavelengths are now extensively used in research directed towards producing new or better lasers. Historically, once the utility of a particular laser wavelength or device has been demonstrated, work often follows immediately towards introducing tuneability and improving the power output and, in the case of pulsed lasers, the repetition rate. Initial X-ray lasers are likely to have poor performance characteristics in comparison to longer-wavelength lasers, while laser-heated plasmas are often irreproducible. When used as the X-ray lasant, troublesome shot-to-shot variation may occur in the X-ray laser pulse. Lack of tuneability and low repetition rates also are likely, and problems may arise with aiming and manipulating the output beam. Another potential problem on the ps time scale could well be synchronisation of of an X-ray laser pulse with equipment which measures the effects of that pulse[62]. It seems a safe prediction that much of the early work with X-ray lasers at least will be aimed at making them reproducible and useful tools with known characteristics. Efforts to improve the output brightness and, especially, to achieve significant temporal and spatial coherence and polarisation will also be important.

Radiation physics, the second application category, is a very broad field. Understanding and theoretically predicting X-ray laser characteristics and the effects of interactions between an X-ray laser pulse and matter falls in this area. However, the thrust here is the consideration of processes involving photons at the high frequencies associated with the soft X-ray region (> 10^{16} Hz). In this respect, theoretical approximations used at lower frequencies may require re-examination. Provided an X-ray laser can be devised, the high fields (intensities) which will become available are probably more important. Strong-field, non-linear effects can also be studied with X-ray laser pulses; although such work must involve interaction with matter, it is likely that the focus of attenuation will be on the radiation and not the material, which can be viewed as a transducer. The few studies in non-linear X-ray effects which have been undertaken to date have involved steady-state measurements with very low count rates[63]. If an X-ray laser were to be used for non-linear experiments, these would require either (or both) parallel-channel recording or multiple pulses because of the short length of an X-ray laser pulse.

The third, and most widely touted, area of X-ray laser application is the probing of matter to determine its atomic and electron structure and its dynamics. The absorption and scattering of X-rays from a laser may be exploited in a variety of ways as discussed in the following paragraphs.

The first historic application of X-rays was in radiography, and pulses from an X-ray laser could well be useful in this respect. The short pulse length involved could be used to 'freeze' very fast motions such as the implosion of laser microballoon targets or the propagation of shock waves in solids. At present, X-rays from laser-heated plasmas are being used for short-pulse radiography (shadowgraphy) of microballoons[64,65]. They could also be used for dynamic studies of the motion in, and of, solids. However a limitation could well be the shallow penetration depth of soft X-rays from a laser in a solid. Flash X-ray diffraction of shock front motion, which is at present achieved with electron-impact flash X-ray devices[66], might also be performed with plasma or X-ray laser radiation. Similarly, diffraction studies of dislocation motion, which now employ synchrotron radiation [67], could be undertaken with single X-ray pulses. Both shock and dislocation motion might be induced with split-off pulses from the same laser as that which pumps the X-ray laser, as shown schematically in Figure 20.12[68]. If a laser-heated plasma is used as the X-ray laser medium, the timing of the X-ray laser probe pulse to the (laser-driven) event of interest might not prove difficult. If this is not the case, then timing could well be a major problem.

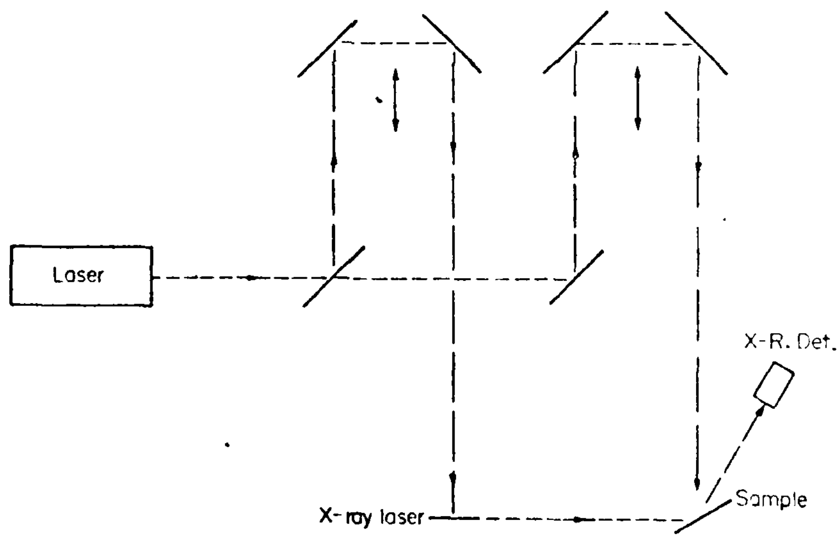

Fig. 20.12 Schematic arrangement for an experiment in which one laser is used to pump an X-ray laser producing a transient effect in a sample (e.g. a shock wave) which is probed by the X-ray laser pulse[68].

Structure determination with short X-ray pulses would overcome the radiation degradation problem which is a major limitation in protein crystallography[9]. However the softness of the X-ray laser output could again be a limitation since diffraction measurements are best undertaken with X-ray energies above 5 keV. A major potential use of X-ray lasers is in holography on an atomic scale as a means of determining molecular structures. However, there are three major barriers to achieving this goal. Firstly, the X-ray laser output beam must have certain definite characteristics, viz. a shorter wavelength than the interatomic spacings being studied plus adequate spatial and temporal coherence. We have already seen that initial X-ray lasers are not likely to have these qualities. Secondly, the object must scatter coherently and specifically. This is a difficult requirement in the soft X-ray region where coherent scattering cross-sections are often small and usually 10^{-3} to 10^{-5} times as large as photo-absorption cross-sections[69]. Radiation damage, even on a ps time scale, is a potential problem since a velocity of only 10^4 cm s^{-1} corresponds to a motion of the order of an interatomic spacing in 1 ps. Thirdly, the recording of an interference pattern with X-rays near 0.2 nm with adequate resolution and sensitivity is a major technical challenge. Photoresists have exhibited spatial resolution capabilities near 10 nm but they are extremely insensitive[70]. Holography of the surfaces of objects using relatively long-wavelength radiation from an X-ray laser recorded on very fine gain photographic emulsion may be possible, although difficult. X-ray holography of objects with dimensions of the order of 10 μm has already been demonstrated using 6 nm radiation from a synchrotron[71] and 0.83 nm radiation from a fine-focus X-ray generator[72].

The probing of electronic structure can be achieved with scattering and emission techniques; thus Compton scattering experiments yield the electron momentum [illegible] distribution in solids. Such experiments would benefit from the monochromaticity of an X-ray laser pulse. However, the long wavelengths of those X-ray lasers which are likely to be produced in the foreseeable future would not be sufficiently penetrating to be [illegible] for Compton measurements in solids. The possibility of stimulated scattering of intense X-ray laser pulses from surfaces could be examined since the emission of electrons or photons due to impact with an X-ray pulse from a laser can yield electronic information. The small spectral width from an X-ray laser would be useful for photo-emission experiments (although the electron analyser window function might prove to be a severe limitation). The short pulse length would permit high-resolution time-of-flight measurements, although space charge effects might interfere. Fluorescence measurements could also be used to exploit both the narrow spectral and temporal widths, especially if a soft X-ray laser were tunable to some extent. Decay times for electronic excitations shorter than 100 ps are now being measured with synchrotron radiation[73], and photonuclear measurements have also been demonstrated with this radiation[74]. If the photon energy of an X-ray laser is sufficient then nuclear fluorescence studies could be of interest. In general terms, the short pulse length of an X-ray laser should prove very useful for the study of the kinetics of excitation and relaxation processes on a sub-ns time scale.

The fourth and most likely area for the use of X-ray lasers is the modification of materials. It was seen earlier that sufficient energy is contained in an X-ray laser pulse to produce significant heating in heavily absorbing materials. X-ray energy could produce electronic excitation, heating, lattice destruction, vaporisation and plasma formation. Since heating and the production of vapours or plasma is readily accomplished by other means, especially the use of long-wavelength lasers, it could well be that lower irradiance X-ray laser effects may be the most important. X-ray effects can be grouped in terms of their progressively longer characteristic times into photophysical, photochemical and, for living matter, photobiological domains. Figure 20.13 is a flow diagram for the absorption, transformation and disposition

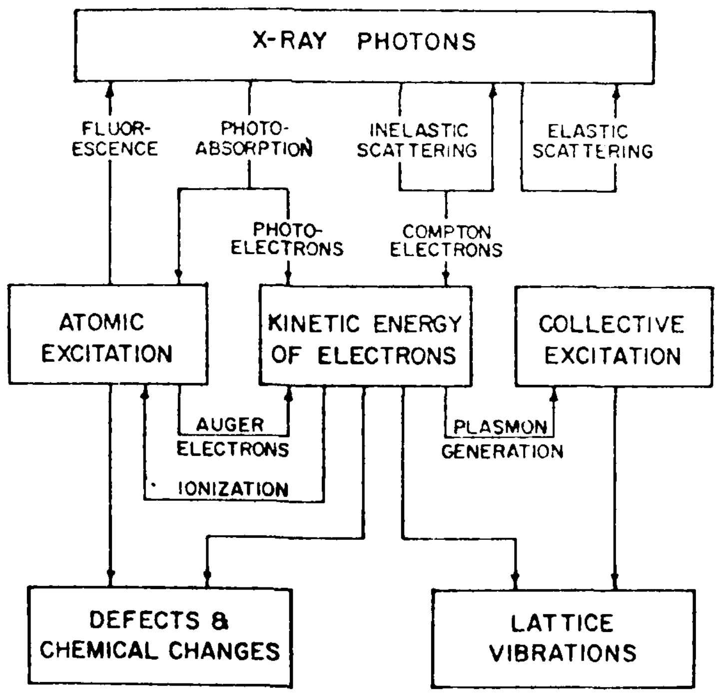

Fig. 20.13 Flow diagram for the photophysical processes by which X-ray photon energy is converted first to electronic vibrations and then to defects, chemical changes and lattice vibrations (heat)[75].

of energy from X-ray photons[75]. An X-ray laser pulse of ps duration would be short in comparison to the characteristic times of some of the processes shown in this figure. Thus, it should be possible to study the dynamics of energy flow through various channels, provided that the means is available to measure with the required time resolution. A short X-ray laser pulse could be useful for studying the basics of X-ray induced effects (damage) in solids. Such damage is an undesirable by-product of microelectronics production by high-energy (X-ray and electron beam) lithographic processes. Molecular photochemical processes driven by an X-ray laser could be interesting both from the fundamental and technological viewpoint.

If coherence could be achieved in an X-ray laser pulse, this could be exploited to produce fine interference gratings. Thus a line pattern with 83.6 nm spacings has been produced in a photoresist by the self-interference of a vacuum-uv (118.2 nm) laser pulse[76]. The radiation-affected regions were dissolved in a developer leavi a corrugated surface. X-ray laser pulses which have been split and reflected off grazing incidence mirrors on to resists could produce fine patterns at the resolut limit of organic resists (possibly 5 nm). It remains to be demonstrated that in-organic resists could have even better resolution. The production of fine (< 10 nm spacing) gratings by the interference of X-ray laser pulses, whilst interesting, would not yield practical, large-area dispersion elements. X-ray lithographic techniques are capable of yielding line-widths of the order of 20 nm[77]. Using spat period division[78], it may be possible to produce large-area gratings with line-widt and separations substantially smaller than 100 nm. Such devices could have groove densities up to 10 times greater than holographically-produced commercial gratings, but their reflection efficiency would probably be low.

The survey of potential applications in the four groupings suggested above prompt some general comments regarding the utility of X-ray lasers, provided that a workable device can be produced. The most important beam characteristics of such a las will be the brightness and short pulse length. The intensity may permit new non-linear X-ray experiments, as well as the study of other small cross-section proces e.g. photonuclear reactions with soft X-rays. We note that the intensity may also be a problem, in that it could produce sample damage. Increasing the laser-to-samp distance or using grazing incidence on the sample will reduce the irradiance with corresponding decreases in the signal and time resolution. High instantaneous data rates and possibly space-charge effects must also be considered. The short pulse length appears to be the greatest near-term advantage of an X-ray laser, if ps time are achieved. Such pulses would be about 10 times shorter than the shortest X-ray pulses from laser-heated plasmas[79]. If a sub-ps X-ray laser pulse can be produced, it may be possible to 'freeze' at least some thermal vibration motions and in this way open up an important new area of research. The monochromaticity of an X-ray laser pulse may be important in time-of-flight photo-emission or photodesorption studies. However, for an X-ray laser to be useful in fluorescence studies, tuneability would be required. The achievement of a coherent X-ray laser output could be very significant, since it would make possible spatial and temporal correlation experiments at high frequencies. The initial drawback of near-term X-ray lasers would be the relative softness of their radiation. X-rays in the 0.1-1 keV range are not penetrating, requiring a vacuum path for propagation in a sample. Also, their long wavelengths preclude most scattering and diffraction (structure determination) experiments of interest.

Some uses of X-ray lasers which have been recommended have been poorly conceived. The likely softness of X-ray laser radiation virtually rules out clinical medical uses, both for radiography and the radiation treatment of disease. High-density information storage (by focussing X-rays from a laser to spots finer than the diffraction limit of light) is certainly not attractive. The low repetition rate of an X-ray laser alone makes such a process impractical, and indeed it is now possible to produce X-ray foci less than 100 nm in diameter using zone plates[80]. Also, it is possible to replicate submicron patterns using X-rays, electrons and ions[81]. An X-ray laser is certainly not needed for X-ray lithography, since plasma sources are adequate for sub-μs exposures over large areas[82]. Indeed, they are so intense that they might produce mask damage[83].

It is quite possible that the list of actual uses of an X-ray laser which would follow the demonstration of such a device would bear scant resemblance to the uses projected above. Some attractive applications might rapidly prove infeasible, at least for a specific early device. And, other uses not anticipated here or elsewhere in the X-ray laser literature would probably be demonstrated. Despite the dangers inherent in technological forecasting, it does seem worthwhile to look ahead in this area. It must be concluded that soft X-ray lasers will not necessarily solve any recognised major problems nor open any large and important new areas of research. Setting aside early enthusiasm, it will take a great deal of work to establish the utility as well as the existence of soft X-ray lasers.

20.7 DISCUSSION

Although direct laser action at wavelengths shorter than 100 nm has not been verified, and some reports of X-ray laser action during the last decade have been contested or discounted, there are at least two reasons to view the work to date with enthusiasm.

Firstly, it has produced a great deal of fresh results in radiation, electronic, atomic, ionic and plasma physics. New insights into ion beams and plasmas have yielded interesting results. Secondly, the research in the 1970s has provided a useful basis for the production of a soft X-ray laser.

In the author's opinion, it appears that direct laser action will be realised in the 10-100 nm region during the 1980s. Several experiments have demonstrated the existence of inverted populations in plasmas by spectroscopic means. Absorption in solids is very high in this region, but plasma media may have regions of adequate transparency to radiation in the 10-100 eV range. Normal-incidence mirrors have significant reflectivities over much of this range, at least up to 30-40 eV. At higher photon energies, multilayer structures produced by evaporation[84] or sputtering[85] yield enhanced near-normal incidence reflectivities[86]. Their use for forming resonators for photon energies in the 30-100 eV range can be expected, either following the slit design of Ilukhin et al.[87] or as free-standing, partially transmissive films. The output end of a cavity lasing in the 10-100 eV region could also consist of a mirror (simple or multilayer) deposited on a smooth, partially-open structure such as a microchannel plate.

Special geometries for the plasma lasant are likely to be used in the 10-100 eV region. Thus linear plasmas have already been studied experimentally for their relevance to X-ray laser research[62] Similarly, special structures near the plasma medium have been employed to interact with the plasma and guide it[88]. Stepped laser targets have also been devised to provide conditions favourable for gain[89]. It is very probable that other specialised geometries will be developed for X-ray laser research. Charge exchange has been shown to be an important mechanism for the production of a population inversion[42]. This suggests new geometries, as shown in Figure 20.14, where a laser plasma could collide with another laser plasma or a laser-produced vapour. One of the collision partners could be replaced by a jet of gas released by a fast-acting valve[90,91]. The geometries shown in the upper diagram in Figure 20.14 are topologically related to the production of a laser plasma in a conical depression, also shown in that figure. Such indented targets have been shown to yield dense plasmas[92]. Colliding plasma geometries might also produce output beams with relatively large cross-sections. Linear interaction regions and travelling-wave pumping are apparently possible with such arrangements. The alternation of timing between the colliding plasma and its partner, and a variation in the composition of one of the colliding clouds, could be powerful tools in the verification of X-ray laser action. The application of external fields to laser-produced plasmas might also be adapted to X-ray laser research, since both

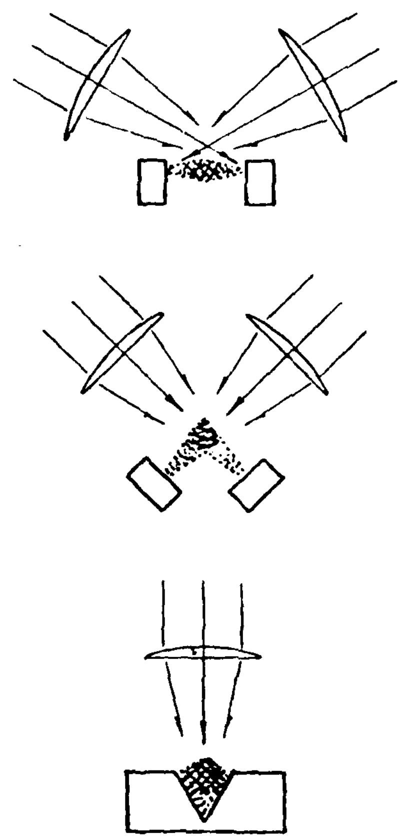

Fig. 20.14 Top and centre: possible configurations for collision of laser-produced plasmas to produce population inversions by charge exchange. One target and laser beam could be replaced with an orifice through which a puff of gas could escape to interact with a plasma. Bottom: related geometry in which a confined and self-colliding plasma is produced by a single laser pulse. Interaction regions, where charge-exchange pumping might occur, are cross-hatched.

electrical[93] and magnetic[94] fields tend to confine laser plasmas. For this reason special geometries combined with external fields may prove useful in the production of an X-ray laser. In any event, colliding and constrained laser-heated plasmas are interesting objects to study.

It now seems much more risky to predict X-ray lasing action in the 1-10 nm (0.1-1 keV) region. Normal-incidence X-ray reflection is still possible in this region but reflectivities may be too small to be useful for resonators, and alignment and mirror damage may well be a problem. The use of adjacent cold materials and applied fields might also be less fruitful with the high-energy-density plasmas needed for X-ray lasing near 1 keV. The fourth-power variation of the required pump power with photon energy presents formidable problems for both pump production and material damage.

If X-ray lasers can be produced in the 10 eV-1 keV region, they should be useful for laser and radiation studies and for the production of changes in materials. Their use for probing materials may be limited to surface studies. To be really useful for the study of the atomic structure of materials, an X-ray laser output above ca. 5 keV is needed. The radiation would then be quite penetrating and the wavelength short enough for important diffraction studies. Also, a hard X-ray laser might have a pulse length much less than 1 ps, possibly short enough to 'freeze' atomic vibrations. Despite its attractiveness, the realisation of a hard X-ray laser seems quite remote at present. It may well be necessary to achieve significant thermonuclear burn in laboratory experiments in order to achieve the energy densities needed for laser action above a few keV.

Nuclear lasers, also called γ-ray lasers or grasers, are not included in this review. Research on such potential devices is quite distinct from work towards X-ray lasers, since it involves nuclear rather than electronic physics. Access to graser literature is greatly facilitated by the recent availability of a bibliography by Baldwin[95]. This author, together with Solem from Los Alamos, is preparing a technical review on grasers with Gol'danskii and Kagan of the USSR Academy of Sciences.

The intense interest in X-ray lasers and γ-ray lasers in the past decade is just one example of activity on a wide range of novel sources, especially those which emit coherent radiation. Some of the mechanisms are observed or postulated to produce only long-wavelength (visible and perhaps uv) radiation, whilst others are relevant to the X-ray region. It is desirable to know the basic physical processes and the status of theoretical and experimental research for each mechanism. In the following paragraphs, a very brief outline is given for several areas of photonics research in which there is intense activity as in X-ray laser research.

Long-wavelength photon sources of recent interest will be mentioned briefly as evidence for the revival of interest in photon sources. Cerenkov radiation (created by electrons which exceed the velocity of light in the medium of travel) and the Smith-Purcell effect (in which electrons moving near a corrugated surface such as a grating emit long-wavelength light) are well understood[96]. More recent, and not so well known, is stimulated emission of shock radiation (SESR) which was predicted theoretically[97]. It involves interaction between counter-propagating energetic electrons and electromagnetic (laser) radiation. The experimental set-up is similar to that for the production of inverse Compton scattering, except that the electron-laser pulse interaction occurs within a gaseous or solid medium. Radiation emitted by the oscillated electrons interacts with (and is slowed down by) the medium, producing a shock front similar to the Mach cone of Cerenkov radiation. Recent calculations show that the intensity of SESR may be much less than originally predicted[98]. Experiments to detect SESR, which is expected in the visible region, are now in progress[99].

There are several other mechanisms and devices in which energetic electrons collide with fields to produce short-wavelength photons. These include the inverse Compton effect and free-electron lasers, transition radiation, coherent Brëmsstrahlung and channelling radiation.

The inverse Compton effect involves the collision of an energetic electron with a low-energy photon to produce a high-energy (X-ray) photon at the expense of electron kinetic energy. Stimulated inverse Compton scattering received renewed attention after the invention of the laser[100], and the possibility of X-ray production by this process was discussed theoretically[101]. In recent years, the process of stimulated inverse Compton scattering has been widely studied as part of the work on free-electron lasers.

Free-electron lasers, which can radiate from the microwave to, potentially, the X-uv region, have received intense interest lately[102]. Ordinarily lasers involve transitions between discrete states, but sometimes the level energies involved can be changed or selected so as to yield tuneable lasers. However, at least one and usually both laser levels have fixed energies. In a free-electron laser, a continuum of energies is available in the kinetic energy of a group of moving electrons. The electron beam interacts with an electromagnetic wave, which may result from the Lorentz transformation of a static magnetic (undulator) field, and the result is electron bunching and cooperative photon emission, i.e., coherent radiation is emitted as a stimulated process similar to an ordinary laser. However, in a free-electron laser the energy which appears as photons comes from the excitation (potential) energy of bound electrons. Free-electron lasers have been realised experimentally using both electrons from a linear accelerator[103] and a hollow beam from a high-power, pulsed electron beam generator[104]. The possibility of free-electron laser action in the X-ray region has been examined recently[107] although, in general, free-electron laser work is not counted as part of X-ray laser research. The wide output range, tuneability and particularly the high potential efficiency of free-electron lasers contribute to their attractiveness.

Several mechanisms of recent interest have already been shown to produce X-rays. When high-energy (GeV) electrons or positrons encounter the few eV potential energy (work function) step at a vacuum-solid interface, they emit transition radiation in the X-ray region[105]. The process is somewhat similar to Brëmsstrahlung emission in that transition radiation emission involves a particle-potential encounter. Transition radiation from single interfaces has been thoroughly studied and is relatively well understood. It was predicted recently that layered synthetic microstructures (discussed above as X-uv optical elements) would produce interesting X-ray spectra when penetrated by GeV particles[106].

Brëmsstrahlung, in which energetic electrons interact with an electronic (nuclear) or magnetic field, has been a well-studied source of X-rays. The same can be said for coherent Brëmsstrahlung, the process by which the radiation amplitudes from two or more simultaneously-active scattering centres add to produce a radiation field different from that of ordinary, single-centre Brëmsstrahlung. (Here, the 'coherence' applies to the X-ray production process and not to the character of the resulting X-rays.) Coherent Brëmsstrahlung is employed to produce pseudo-monochromatic, very high energy (GeV) photons. It has also been studied at lower electron energies (MeV) and photon energies (keV), both theoretically[107] and experimentally[108]. Coherent Brëmsstrahlung is receiving reviewed attention because of recent work on channelling radiation. The latter results when positrons[109] or electrons[110] propagate and oscillate between planes or along atomic rows in highly-perfect single crystals. Channelling radiation, like coherent Brëmsstrahlung, produces X-ray spectra with broad peaks, in contrast to the smooth continuum of ordinary Brëmsstrahlung. Uberall has recently developed a formalism embracing the production of both coherent Brëmsstrahlung and channelling radiation for electron or positron motion in single crystals[111].

Das Gupta has observed discrete frequencies in the Brëmsstrahlung continuum which appear somewhat like those from coherent Brëmsstrahlung or channelling radiation[112]. Energetic electrons (e.g. 450 keV) striking inside cylindrical cavities, produce collimated radiation independent of the wall material. Peaks were observed at six energies in the 20-350 keV range. The reported values correspond (within experimental error) to energies at which an integral number of de Broglie electron wavelengths match the Brëmsstrahlung short-wavelength limit. However, experiments at other laboratories to verify Das Gupta's results did not provide confirmation [113,114]. The peak energies were contested and ascribed to a variety of causes, such as Compton scattering. Also, since some of the cylindrical targets used by Das Gupta were non-crystalline (glossy), it is difficult to ascribe the reported peaks to coherent Brëmsstrahlung or channelling radiation. Most recently, Das Gupta has repeated and extended his measurements. He finds that the peak positions are independent of electron energy in the 0.5-1 MeV range[115].

A second set of measurements by Das Gupta, apparently related to the production of an X-ray laser, has not received additional experimental attention. He and his colleagues have observed both a non-linear variation of X-ray intensity with electron current[116] and line-narrowing[117] in measurements with a polycrystalline anode microfocus X-ray tube. The CuK α_1 and α_2 intensity (above an extrapolation of the low current data) varies approximately as the fifth power of the current[118]. Nonlinearity with pump power and line-narrowing are characteristics of, and tests for, lasing. But the power densities in Das Gupta's experiments were far below those computed to be necessary to overcome the short lifetimes in the hard X-ray region. The microfocus experiments should be performed at other laboratories with single-crystal anodes in order to verify and extend Das Gupta's observations.

The X-ray emission processes discussed in this section can be viewed and classified very generally according to (i) energy and density (current) or the charged particles (usually electrons); (ii) the frequency of the interacting electromagnetic wave, in cases such as the free-electron laser; and (iii) the density (periodicity) of matter, in cases such as coherent Brëmsstrahlung. The object of reviewing the various processes in a paper on X-ray laser research is to document the generally high level of interest in basic research on new X-ray sources. Intense sources such as GeV storage rings and multimillion degree plasmas are now quite well understood and used extensively for atomic, molecular and condensed matter research. It is reasonable to anticipate the development and use of even more intense and also coherent X-ray sources, especially if an X-ray laser can be achieved.

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