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REVIEW OF SOFT X-RAY LASERS AND THEIR APPLICATIONS

BY

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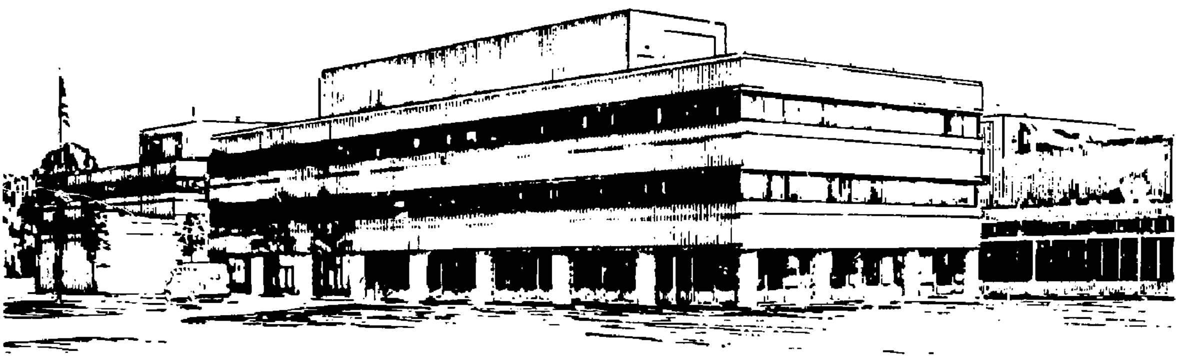

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Review of Soft X-Ray Lasers and their Applications

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The emerging technology of soft x-ray lasers is in a transition phase between the first laboratory demonstrations of gain and the acceptance of soft x-ray lasers as practical tools for novel applications. Current research is focussed on several fronts. The operational wavelength range has been extended to the "water window", important for applications in the life sciences. Gain has also been generated with substantially simpler technology (such as a 6J laser) and this augurs well for the commercial availability in the near future of soft x-ray lasers for a variety of applications. Advanced soft x-ray laser concepts are being developed from investigations into ultra-high intensity laser/matter interactions. The first applications of soft x-ray lasers to x-ray microscopy and holography have begun. In this paper a brief historical perspective of x-ray laser development will be followed by a review of recent advances in recombination, collisional and photo-pumped systems and applications. A summary of current gain-length performance achieved in laboratories worldwide is presented. Near term prospects for applications to novel fields are discussed.

I. INTRODUCTION

After the first conventional laser was demonstrated by Maiman[1] in 1960, the directionality and brightness of these new light sources caught the public imagination but they were slow to find applications. In fact, there was an extended period when they were known as "solutions looking for a problem." Today of course, 30 years later, the situation is very different with laser scanners in widespread use in retail stores, and lasers in compact disk players and even in dentists' offices. It is now six years since the first demonstrations of lasing in the soft x-ray region and we are currently in a period between the generation of gain in many different systems and the acceptance of x-ray lasers as practical and useful tools. The historical development of conventional[2] and soft x-ray lasers and their applications is illustrated in Fig. 1.

One of the earliest applications of the first conventional laser, the ruby laser, was for repairing detached retinas. This came about because xenon lamps were already being used for this purpose, and the replacement of xenon lamps with lasers was a straightforward extension of the technique. X-ray lasers are following the same pattern. In the applications emerging at present, such as x-ray microscopy, soft x-ray lasers are being applied to an existing technique because they have a significant advantage compared to present sources. However it is clear from the precedent of visible lasers that the most revolutionary applications of x-ray lasers will turn out to be ones undreamt of at the present time.

A key factor in the range of practical applications of x-ray lasers is their cost and significant progress has been made in the development of moderate cost x-ray lasers. In fact, it is the performance requirements of applications that are driving the development of x-ray laser technology. The task at hand is to demonstrate to the potential user community that soft x-ray lasers are not just exotic and expensive specialized laboratory phenomena but can be practical tools with important applications.

In this paper, a brief historical perspective of x-ray laser development will be followed by a review of the two most successful methods to generate lasing: recombination and collisional pumping. These two schemes continue to make rapid progress in extending the wavelength range and performance of soft x-ray lasers. Significant recent achievements in collisionally pumped systems include (i) the generation of high gain-lengths near the carbon K-edge[3]: a gain-length of GL=8 at 44.8Å in Ni-like tantalum, important for the application of x-ray lasers to the holography of biological cells, and GL=7 at 43.18Å in Ni-like tungsten, the first soft x-ray laser operating within the "water window" wavelength region important for x-ray microscopy; and (ii) the demonstration of high gain-lengths at 232Å and 236Å in less technogically demanding Ne-like germanium systems[4] at several laboratories world wide. Recombination soft x-ray lasers have already been applied to the microscopy of biological cells[5]. The higher efficiencies of recombination schemes continue to spur progress and high gain has been achieved in H-like carbon plasmas with only 6-15J pump laser energy.[6,7] Although more work needs to be done to maintain this high gain over large plasma lengths, this result augurs well for the commercial availability in the near future of moderate cost x-ray lasers for a wide variety of applications.

The availability of efficient dielectric mirrors was crucial for the development of conventional lasers; in fact many of the new lasers simply would not have lased without them. Thus it is very timely that a parallel "revolution" in x-ray optics[8] is providing the tools for cavity development for ultra high brightness x-ray lasers and for the manipulation and focusing of x-ray laser beams for applications in ways completely analogous to those of conventional optics.

Previous reviews of x-ray lasers and their applications are given in references 9, 10 and 11 and advances in x-ray optics have been reviewed in reference 8. The most current exposition of x-ray laser technology in this rapidly advancing field will be the Proceedings of the 2nd International Conference on X-ray Lasers which will be published in the Spring of 1991.[12] The present paper will build on reference 9 to review the current status of soft x-ray laser technology with particular attention to improvements in performance (wavelength range and gain), progress in the simplification of the technology required, and the status of soft x-ray laser applications.

II. SOFT X-RAY LASERS

Just three years after the invention of the ruby laser, a paper[13] appeared in the Russian literature drawing attention to the potential of recombining plasmas for the generation of gain. Several seminal papers on new schemes to generate x-ray lasing followed based on (i) innershell photo-ionization,[14] (ii) collisional excitation in neon-like ions[15] and (iii) photopumping.[16] A necessary condition for the generation of gain is a population inversion and this step was achieved in 1974 although the density in this experiment[17] was too low for measurable gain. Pioneering work on the generation of gain in recombining plasmas produced from laser heated carbon fibers was reported by Jacoby et al.[18] in 1981. However the current period of intensive work on soft x-ray lasers began with the 1984 announcement at the 26th Annual Meeting of the American Physical Society Division of Plasma Physics of the first demonstration of lasing action in the soft x-ray region by groups at Lawrence Livermore National Laboratory[19] and Princeton University.[20]

These two groups used different approaches to generate gain (see Fig. 2) and these have formed the basis of the successful work on soft x-ray lasers since that time. They are:

(i) the recombination approach based on hydrogen-like or lithium-like ions

(ii) the collisional excitation approach based on neon-like or nickel-like ions.

Both schemes rely on a high power pulsed laser to create the appropriate conditions in a plasma and in both schemes the population inversion necessary for stimulated emission and gain is brought about by fast radiative decay of the lower level. Another common feature is that the ion ground state from which the population inversion is supplied has a closed shell (Ne or Ni-like ions for the collisional scheme; He-like or bare ions for the recombination scheme). Closed shell ions have a high fractional abundance in plasmas and this aids the generation of high gain.

In the recombination approach for hydrogen-like ions, a laser is used to create a plasma with a high fraction of totally stripped ions. After the laser pulse, the plasma is cooled rapidly and undergoes fast three-body recombination. In some cases the plasma is cooled by adiabatic expansion. One unique feature of the Princeton laser is that the plasma is confined in a magnetic field and cooled by radiation losses. The magnetic field maintains a high electron density which is beneficial as the three body recombination rate scales as the electron density squared. It also helps shape the plasma into a long thin geometry suitable for a laser. Three-body recombination puts a high population into upper excited levels which decay downward by collisional–radiative cascade. In hydrogenic ions level 2 decays rapidly by radiation and a population inversion is built up between levels 3 and 2. The atomic structure of lithium-like ions is similar to hydrogen-like ions and the same approach works there also.[21,22] In this case the 3-2 transitions have a high radiative decay rate and gain can be generated on the 4-3 and 5-3 transitions. The lithium-like sequence has the advantage of a shorter wavelength lasing transition for ions of similar ionization potential, i.e., a better "quantum efficiency."

The neon-like collisional excitation scheme was applied by Lawrence Livermore National Laboratory. Here a high density, high temperature plasma is generated by a large neodymium laser, Novette or Nova. In the neon-like plasma, a large population of ions is collisionally excited to the 3p level. The 3s level has a relatively low population since it has a fast radiative transition to ground and a population inversion is built up between the 3p and 3s levels. Other kinetic processes, such as dielectronic recombination, play a role in determining the relative gain of the various lines between the 3p and 3s levels. The same scheme also works in nickel-like ions[23] and here, as in the case of lithium-like ions, there is an advantage in using the nickel-like sequence to access the shortest possible wavelengths. A review of work at Livermore is given in reference 10. In summary, both approaches use a high power laser to create an appropriate plasma and rely on fast radiative decay to deplete the lower level in order to generate a population inversion. The major difference is that in one case the upper level is populated through recombination and the other by collisional excitation.

Intensive efforts at laboratories worldwide have resulted in gain being demonstrated over a wavelength range from 35Å to 326Å in a variety of systems. From the point of view of applications, the "figure of merit" of these achievements depends on which particular application is being considered. However, one widely reported performance parameter is the gain-length product, GL. This is related to the enhancement, E, of the output intensity compared to spontaneous emission, by the relation:[24]

$$E = \frac{(e^{GL} - 1)^{3/2}}{GL\,(GL\,e^{GL})^{1/2}} \qquad (1)$$

which describes the enhancement of output intensity (stimulated/spontaneous emission) of a Doppler broadened, homogeneous source of amplified stimulated emission of gain-length, GL. This is plotted in Fig. 3 and one can see that it is only when the gain-length exceeds GL = 4.6 that the output intensity exceeds spontaneous emission by more than an order of magnitude. High gain-lengths have been achieved over a range of wavelengths and the state of the art in November 1990 is represented in Table I and Fig. 4. Recent highlights will be discussed in the following sections with particular attention to measurements of gain at new wavelengths and advances with special significance from the point of view of applications.

III. RECOMBINATION SYSTEMS

Recombination schemes have the advantage of a $\Delta n=1$ lasing transition (where n is the principal quantum number) which scales rapidly to shorter wavelengths with increasing ion charge, z. They also have a higher efficiency than the collisional schemes. Recently gain has been observed on the CVI 182Å transition with remarkably low pump energies (6 - 15J).[6] A Nd/YLF laser beam was line-focussed onto a carbon target and a thin iron blade in the front of the target provided additional cooling of the plasma column. Gain of up to $G \approx 8\ cm^{-1}$ was demonstrated in one amplifier with 15J of Nd/YLF laser beam energy on target. In this experiment the axial spectrum in the vicinity of the gain line, the CVI 182Å 3-2 transition and in the vicinity of CVI 135Å 4-2 transition, was measured for 1, 2, and 3 mm long targets. A striking, non-linear increase in intensity of the 182Å gain line with length was observed in comparison to the linear increase in intensity of the 135Å spontaneous emission line. Subsequent experiments[7] with only 6 J of pump laser energy also showed $g \approx 4.5 cm^{-1}$. Currently, work is in progress to extend this to longer plasma lengths[25] (see Fig. 5) so that a high gain-length and high output can be achieved. The successful commercial development of these kinds of lasers would greatly extend the range of viable applications of soft x-ray lasers.

Recent work at the Institute for Laser Engineering at Osaka has extended the wavelength range of the recombination Balmer α laser down to 54.2Å using hydrogen-like NaXI.[26] A foil target (4500Å of NaF on CH) of length up to 0.45cm was illuminated by a 18J, 20psec laser pulse at 526nm resulting in gain of $8.6 cm^{-1}$. The stimulated emission was refracted 10mrad away from the plasma axis by density gradients in the plasma thus limiting the gain-length, however a solution to this problem has been demonstrated experimentally in collisionally excited systems (see Section IV). An alternative approach to overcome refraction is to use double foil targets.[27] In this case, the concave electron density profile has a waveguiding effect on the propagation of the soft x-ray beam. At the Rutherford-Appleton Laboratory gain has been observed on the fluorine Balmer α transition at 81Å by illuminating a lithium fluoride coated carbon fiber with a 70psec laser pulse.[28] This experiment has been modeled with a 1D hydrodynamic code[29] which predicted a value of gain less than half that observed. There has been some speculation that this and other discrepancies between experiment and modelling is due to an unrealistic treatment of radiation trapping but so far this has not been resolved.

From the point of view of applications it is encouraging that the operating range of recombination systems is being extended to the region below 100Å. With proper control of plasma uniformity and refraction higher gain-lengths should be possible in these systems so that the output intensity is suitable for applications.

IV. COLLISIONAL EXCITATION

Significant progress has been made in extending collisional excitation schemes to shorter wavelengths. The pump laser power requirements were predicted to scale as λ^{-4} which is quite costly.[30] However gain of 7.5 ±2 cm^{-1} at 99Å has been reported[31] in Ne-like silver using a laser power of 9 $\times 10^{14}$ Wcm^{-2}. Ni-like systems have a higher quantum efficiency than Ne-like ions and a gain-length of GL=7 has been demonstrated at a wavelength of 43.18Å in Ni-like tungsten[32] (see Fig. 6). This is the first demonstration of a x-ray amplifier on the short wavelength side of the carbon K edge, within the "water window" important for x-ray microscopy. At a slightly longer wavelength of 44.83Å, a gain-length of GL=8 has been achieved in Ni-like tantalum. This is an ideal wavelength for holographic imaging of cellular material.[33] We will return to this topic in Section VII B.

The above results in collisional systems were achieved using high power second harmonic (2ω) illumination on foil targets. High gain has also been demonstrated in collisional systems using less demanding technology; in particular gain in neon-like germanium at 196Å, 232Å, and 236Å has been achieved using slab targets with single-sided 1ω illumination.[5] In fact the gain using 1ω illumination on germanium slab targets was higher than using 2ω on germanium foils.[34] This system has gained the reputation of being a "poor man's neon-like x-ray laser" and has been demonstrated at a number of institutions.[35-37]

Recent work has utilized the information gained in characterizing the output beam to address the refraction problem.[38] Density gradients perpendicular to the slab target surface had caused refraction of the stimulated emission out of the gain region with long target lengths. However when two germanium targets were illuminated from opposite directions with a 800J, 620psec pump laser, the reversal in direction of the density gradients in the second plasma corrected for the refraction in the first plasma so that the stimulated emission from the first 22mm plasma could be amplified by a factor of ×50 by the second 14mm plasma. The estimated output power on the 232Å and 236Å lines was close to 1MW. The duration of the output was 60 to 80% of the pump laser duration of 0.5 or 1 nsec.

This has encouraging implications for future cavity development since a multi-nanosecond output would allow several cavity round trips and an output of good spatial mode quality.

A proposal to develop a "table top" soft x-ray laser is under investigation at MIT.[39] This is based on the collisional excitation scheme in nickel-like molybdenum. Modeling predicts that transient gain may be produced with a pump energy of only 10J. As with the CVI 182Å recombination system, such a small-scale laser would be attractive from the point of view of applications.

V. PHOTO-PUMPED AND DISCHARGE PUMPED SCHEMES

Photo-pumping is predicted to generate gain when intense line emission from one ion selectively populates an upper lasing level in a different ion by resonant photo-excitation. In this, it is distinct from recombination or collisional schemes which rely on the selective *depopulation* of the lower lasing level to generate a population inversion. The pump source can be excited by a laser or a discharge. The separation of pump and target plasmas offers the opportunity for the individual optimization of each, however the optical coupling between separate plasmas can be inefficient. An essential requirement in resonant photo-pumping is a wavelength coincidence ($\Delta\lambda/\lambda \approx 10^{-4}$) between the pump and pumped transitions and a list of suitable lines is given in Ref. 11.

A surprising recent result has come from work on neon-like titanium.[40] Gain of 2.7cm^{-1} at 326Å was measured on plasmas of length up to 2.2cm (Fig. 7). At first sight this looks like another example of the neon-like collisional pumping scheme but this laser is distinct from the other neon-like systems in several ways. The dominant lasing line is the $J=0\rightarrow1$, $3p\rightarrow3s$ transition while the $J=2\rightarrow1$ transition shows no gain. In contrast, the dominant lasing line in other neon-like lasers is the $J=2\rightarrow1$ transition. The 326Å laser output has an unusually narrow divergence and lasing is only observed when the main optical pulse is preceded by a low intensity prepulse. Nearby elements V(z+1) and Sc(z-1) do not lase under the same conditions. These factors have led to the suggestion that the gain is generated by resonant photopumping of the Ne-like Ti $2p\rightarrow4d$ transition by the $3s\rightarrow2p$ C-like and $3d\rightarrow2p$ N-like

Ti lines. If confirmed, this would be the first example of a new class of soft x-ray lasers pumped by photo-excitation.

A more traditional photo-pumping scheme uses the 11Å $1s^2$ - $1s2p$ $^1P_1$ line of NaX to pump the $1s^2$ - $1s4p$ $^1P_1$ line of NeIX[16] as these wavelengths match to 2 parts in 10^4. This requires a pump power of 150-200 GW for a practical gain demonstration.[41] This power level has now been attained in large pulsed power devices at Sandia and at Physics International and first indications of fluorescence on the pumped lines have been observed.

Another interesting development is work on capillary discharges to create plasma conditions suitable for generating soft x-ray gain.[42] The advantage of discharge pumping is that it is technically simpler and of higher efficiency than large-scale laser drivers and this translates into potentially lower cost. The range of practical applications of soft x-ray lasers is strongly dependent on their cost so discharge pumping is an attractive prospect for commercial development of x-ray lasers. Hybrid capillary discharge/laser schemes have also been proposed.[43]

Laser produced plasmas generated by two parallel line foci in different target arrangements have been investigated by Fill and coworkers.[44] The close proximity of pumping and target plasmas in this geometry is advantageous for the efficient coupling of the radiation. A factor of two increase in emission has been observed due to photo-excitation and pump intensities have been estimated at 10^{-3} photons/mode. In the relatively unexplored XUV region, a photo-pumped laser at 600Å has been proposed[45] and is under development at Princeton.[46]

VI. SOFT X-RAY OPTICS

The ability to manipulate and focus a soft x-ray laser beam is crucial for many applications. Fortunately rapid developments in the field of soft x-ray optics are providing tools such as normal incidence mirrors, beam splitters and diffraction limited lenses for sophisticated soft x-ray optical systems.[8] Mirrors are fabricated by alternating layers of high and low z material (e.g., molybedenum/silicon) on an ultra smooth substrate. They were first used to amplify reflected soft x-ray stimulated emission in a second pass through the gain medium by Keane et al.[47] A sophisticated demonstration of triple-pass amplification was reported by Ceglio et al.[48] Encouraging progress has been made in fabricating mirrors for use around 44Å in the difficult "water window" region.[49] Much of the high brightness and hence utility of conventional lasers arises from the optical cavity which enables the energy to be extracted in a low divergence beam. An unstable resonator soft x-ray cavity[50] with a single mode output would have a brightness many orders of magnitude higher than the amplified spontaneous emission (ASE) from existing soft x-ray lasers since at soft x-ray wavelengths the diffraction limit for the laser divergence is of the order of microradians. Technical issues such as the survivability of mirrors in close proximity to the plasma seem to be in hand, and work is in progress to control refraction in the gain medium.[27,38] X-ray oscillators have been designed to avoid limits on gain duration by multi-pulse synchronous pumping in regenerative amplifier systems.[51,52] The near term prospects for a high-brightness x-ray laser using a cavity look very promising.

VII. APPLICATIONS

A. Soft X-ray Laser Microscopy

Present knowledge of the internal structure of cells has been largely gained by the development and application of the techniques of electron microscopy. This knowledge rests on the premise that the intensive procedures necessary to prepare a specimen for electron microscopy do not significantly influence the detailed structure observed. Nonetheless, unanswered questions remain about the fidelity of an image of a cell that has been fixed, stained with heavy metals and sectioned, to the original living cell. X-ray microscopy offers a new way to look at unaltered cells in their natural state. This comes about because the absorption edges in the x-ray spectra of naturally occurring cell constituents provide contrast without the addition of heavy metals to the cell, necessary in electron microscopy. Biologists have long dreamt of observing the form and function of *living* cells at high resolution. Work has begun using high brightness synchrotrons and soft x-ray lasers as light sources for x-ray microscopy.[53] Remarkable images of cells have been obtained using soft x-rays from synchrotrons, however the exposure time is a fraction of a minute. The special advantage of soft x-ray lasers is that their short, nanosecond pulse length offers the potential of observing a cell that was alive the instant before a flash exposure of a soft x-ray laser, thus radiation damage or movement of cell constituents will not be apparent in the image. The necessary radiation dose levels make it unlikely that the cell will survive the exposure but images of different cells should make it possible to piece together new information about dynamic processes inside cells.

Work has begun at Princeton using the 182Å laser[20] for soft x-ray contact microscopy of biological specimens with the ultimate goal of obtaining images of living cells.[5] This work is also closely related to X-ray microlithography. In the X-ray laser contact microscope, a thin (~0.1 μ) silicon nitride window separates the vacuum tube, in which X-rays travel, from the biological cells located on photoresist at atmospheric pressure. Recording the image on photo-resist is necessary for high resolution and it has been demonstrated that the 182Å laser beam has sufficient energy to expose images on photoresist in a single shot. The "water window" region between the oxygen and carbon K edges (23Å - 44Å) is customarily regarded as ideal for x-ray microscopy, however at 182Å the absorption cross section of oxygen is three times that of carbon providing contrast between carbon in the cell proteins and the oxygen in the surrounding water. In x-ray contact microscopy magnification is obtained when the exposed photoresist is viewed in a scanning electron microscope. Images of diatom fragments (the silicified skeleton of planktonic algae) on photoresist have indicated the resolution on the photoresist was better than 0.1 μm. One may also regard diatom fragments as a type of lithographic mask and an illustration of the potential application of the soft x-ray lasers to microlithography.

A Composite Optical/X-Ray Laser Microscope (COXRALM) has been built. This was designed to allow a biologist to select and observe live cells using an optical phase contrast microscope[54] and then create a high resolution image of the cells on photoresist with the soft x-ray laser beam. The first results were obtained with unstained dehydrated cells to optimize image contrast and resolution without the technicalities of handling wet/live cells. Fig. 8 shows a scanning electron microscope image of a replica, produced by the 182Å soft x-ray laser, of dehydrated hela cells (Helen Lane cervical cancer cell) obtained from the Biology Dept. of Princeton University. Presently this work is concentrated on experiments with cells in a wet environment.

Spontaneous emission from plasmas has also been used for contact soft x-ray microscopy,[5,55] however the output is broadband and uncollimated. For advanced microscope designs in which narrow band multilayer mirrors are used to manipulate the soft x-rays, a monochromatic soft x-ray laser has a clear advantage. Such an Imaging Soft X-Ray Laser Microscope ("IXRALM") is under development at Princeton.

B. Soft X-ray Laser Holograpy

The prospect of high resolution, three-dimensional imaging of biological cells has excited the imagination of microscopists since the 1950s. However, only with the advent of high brightness x-ray lasers and undulators together with the necessary x-ray optics did the promise begin to become a reality. In 1987 the first hologram with sub-micron resolution was achieved using an undulator at Brookhaven[56] and, almost simultaneously in a completely different experiment, a hologram using a flash subnanosecond exposure was produced from the 206Å and 209Å selenium soft x-ray laser.[57] As with soft x-ray microscopy, the clear advantage of nanosecond x-ray laser sources is in avoiding the problem of blurring of the image due to motion (possibly due to radiation damage) during the exposure. The optimum wavelength for soft x-ray holography of biological structures in an aqueous environment turns out not to be in the "water window." Wavelengths slightly longer than the carbon K-edge provide an optimal trade off between minimizing the necessary source power and the dose absorbed by the sample and maximizing the penetrability of x-ray through wet samples.[33] An additional advantage is that it is possible to use carbon in multilayer optics at this wavelength.

Intensive work in extending the wavelength range of collisional excitation x-ray lasers has achieved high gain-length (GL=8) in nickel-like tantalum at 44.83Å[3] and a major effort is underway to develop x-ray laser holography for three-dimensional high resolution imaging in structural biology.[58] Serious technical challenges remain however. Single mode laser operation is required whereas the current tantalum amplifier is expected to have $\approx 10^4$ modes because of its large Fresnel number. Increasing the gain-length to GL≈22 in a mode-selective double-pass arrangement is planned to achieve the 10-100 μJ/mode coherent output required. The main attraction of holography is three-dimensional imaging, however depth resolution requires illumination over a large solid angle (the depth resolution is less than the transverse resolution by a factor of 1/sinA where sinA is the numerical aperture of the illumination). For this reason multiple beams are planned to illuminate the sample over a large solid angle. The requirements on x-ray optics will be most demanding. Nonetheless the rapid progress to date is encouraging evidence that three-dimensional imaging of, for example, a human chromosome will be within reach in the near future.

C. Other Applications

Besides microscopy and holography, a wide variety of other applications of x-ray lasers to science and industry have been proposed. Scientific applications include the new field of non-linear phenomena at x-ray wavelengths. Conventional lasers heralded a revolution in the understanding and application of non-linear optics in the UV to IR wavelength range. The focussed output power that should soon be available from a saturated x-ray laser, exceeds 10^{14} Wcm^{-2} raising prospects for efficient harmonic generation.[8] The possibility of a tunable x-ray laser through four-wave mixing with an optical laser is being investigated.[59] Such a tunable x-ray laser would offer opportunities for elemental analysis and fluorescence studies. Attempts have been made to use photo-ionisation to down-convert the x-ray emission to the XUV[60] and frequency up-conversion to shorter x-ray wavelengths has been studied.[61] Soft x-rays penetrate plasmas with electron densities as high as 10^{22} cm^{-3} and offer new possibilities in plasma diagnostics.

An industrial application with clear analogy to x-ray microscopy is x-ray lithography; however the use of a x-ray laser in an integrated circuit (IC) production facility would require a much more efficient x-ray laser with an average power of ≈100mW. A more immediate application may be in the lithographic inspection. Another application is the fabrication of holograms such as ultra-fine diffraction gratings.

VIII. ADVANCED X-RAY LASER SCHEMES

Advances in subpicosecond laser technology in the optical wavelength range have led to the availability of laboratory-scale lasers with focussed power densities exceeding 10^{18} Wcm^{-2}. At these intensities the electric field in the focussed laser beam exceeds the Coulomb field between the electron and nucleus in the hydrogen atom and intensive work is being done to understand the physics of laser-matter interactions at these ultra-high intensities.[62-67] The pump power required to generate gain at shorter wavelengths scales as λ^{-3} - λ^{-4} ; principally due to depopulation of excited states by spontaneous emission. This means, for example, that the pump power needed for a 10Å laser is 10^3 – 10^4 higher than for a 100Å laser. The radiative lifetime scales as λ^{-2} and is of the order 10fsec for a 10Å transition so clearly an ultra-high power subpicosecond pump laser is appropriate to the task of creating a ≈10Å x-ray laser. Since the required pump energy now scales only as λ^{-1} the cost is not prohibitive. A population inversion on a x-ray transition is an example of an extreme non-equilibrium situation but the extreme spatial and temporal gradients in a focussed ultra-high intensity femtosecond pulse are suited to this task. One approach is to scale the recombination scheme to shorter wavelengths. Here the UV wavelengths of the powerful subpicosecond lasers allow access to appropriately high densities and the short pulse length permits the picosecond cooling time required to generate gain by adiabatic expansion. Other proposed schemes are based on multiphoton ionisation,[64,68] inner shell ionisation[14] and Auger transitions.[69]

A novel two laser approach to x-ray lasers in the 10-50Å region is under development at Princeton.[70] Here a conventional high energy (Nd or CO_2) is used to create a target plasma of the appropriate state of ionization which is then excited by a powerful subpicosecond pulse. The high energy laser efficiently generates the high ionization stages required and non-linear processes are excited by the powerful subpicosecond laser. First experiments using a x-ray streak camera have clearly shown the interaction of the subpicosecond pulse with the pre-formed plasma. When the subpicosecond laser alone is focussed on a teflon target the spectrum of the plasma emission shows resonance lines of hydrogen-like carbon with enormous Stark broadening (see Fig. 9), corresponding to electron densities up to 10^{23} cm^{-3} and indicative of the extreme conditions these lasers can produce.

We would not like to leave this section on laser development without mentioning recent progress in XUV lasers. A 1089Å xenon laser based on photo-ionisation pumping has been developed which has achieved a saturated output with only 0.5J of pump energy at a repetition rate of 2 Hz.[71] In a similar experimental setup an atomic cesium laser with a gain-length product of GL=85 has been produced, in this case collisional excitation by photo-electrons created the population inversion.[72] The XUV wavelength region was originally overlooked in the race toward x-ray lasers but this region has important applications in chemistry.

IX. FUTURE OUTLOOK

The quest for X-ray lasers has fostered research that has deepened our understanding of fundamental atomic, plasma and optical physics. Soft x-ray laser technology is relatively young but is already being applied to existing fields most notably x-ray microscopy and holography. Soft x-ray lasers have been developed with an energy sufficient to expose record high resolution images on photo-resist or with a brightness 6 orders of magnitude higher than existing or planned synchrotrons. The first results from the applications to microscopy and holography are in hand. Current research efforts are proceeding on two fronts. Encouraging progress has been made at large laser facilities to extend the operating range to shorter wavelengths. The complexity of the pump lasers used at these institutions will lead to a "user facility" situation for potential users, somewhat similar to present arrangement with synchrotrons. In parallel, efforts are being made to simplify the technology required for soft x-ray lasing, for instance by using low energy pump lasers to generate gain. Alternatively, discharge pumping may in the future greatly reduce the complexity and hence the cost of these devices. Cost is a crucial factor in the utility of these devices and the range of potential applications. These two (large-and small scale) approaches may well co-exist in a manner analogous to National Supercomputing Centers and Personal Computers. Parallel developments in x-ray optics will play a crucial role in realizing the maximum brightness of these devices with cavity optics and in manipulating the beam for applications. Efficient normal incidence mirrors for the "water window" region and multilayer coatings on curved focussing optics and waveguides are important current research efforts.

While recent progress in soft x-ray lasers and optics has been remarkable, the advent of useful devices based on this technology will not be automatic. It needs sustained and consistent funding which is dependent on a political will and public recognition that future prosperity cannot be assured without investment in long term research and development. The increasing maturity of the international effort in x-ray laser research together with cutbacks in the U.S. funding may result in leadership in this promising field going overseas. This political challenge may well turn out to be the pacing item in the continued progress in this field.

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Figure Captions

Fig. 1 Historical perspective comparing the development of conventional lasers and their applications to soft x-ray lasers.

Fig. 2 Partial energy level diagram of recombination and collisional pumped soft x-ray lasers.

Fig. 3 Plot of eqn. 1 showing the output intensity as a function of gain-length expressed in terms of the enhancement of stimulated emission over spontaneous emission levels.

Fig. 4. Gain-length achieved versus wavelength from table 1. The hair line marks GL = 4.6 which corresponds to an enhancement of 10. Note that the y axis is approximately logarithmic in intensity (eqn.1) so that the points in the upper half of the graph represent extremely bright sources.

Fig. 5 Intensities of the CVI 182Å and 135Å lines versus plasma length and (dashed line) a least squares fit to a gain of $4.5 cm^{-1}$ for the 182Å line.

Fig. 6 On-axis spectra from 2.5- and 1.7-cm-long tungsten foils. The 2.5-cm foil had a gain-length product of GL=7 at 43.18Å.

Fig. 7 On-axis spectrum from a 3.8cm titanium target. The laser line at 326.5Å dominates the spectrum. Two weaker lines are seen at 473.2Å and 508.8Å. Note the absence of the $J=2 \rightarrow 1$ lines which are expected at 459.4Å and 472.1Å.

Fig. 8 An image produced by the 182Å soft x-ray laser of Helen Lane cervical cancer cells.

Fig. 9 Spectra obtained from the interaction of a powerful subpicosecond laser of intensity of 2×10^{18} $W cm^{-2}$ with a teflon target; (a) spatially integrated spectrum showing well defined satellite lines, and (b) spectrum emitted close to the target surface showing very broad CVI 33.7Å emission.

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TABLE I. Performance of systems exhibiting soft-x-ray gain at laboratories around the world as of 11/90

Wave-length (Å)	Institution	Ref.	Element	Gain-length	Wave-length (Å)	Institution	Ref.	Element	Gain-length
35.6	LLNL	73	Au 52+ (Ni-like)	3.0	182	ILE	26	C 5+ (H-like)	2.6
43.2	LLNL	32	W 46+ (Ni-like)	7.0	182	LLNL	10	Se 24+ (Ne-like)	9.6
44.3	LLNL	32	Ta 45+ (Ni-like)	8.1	182	NRL	80	Se 24+ (Ne-like)	3.1
50.2	LLNL	10	Yb 42+ (Ni-like)	2.0	182	LLE	81	C 5+ (H-like)	4.1
54	ILE	26	Na 10+ (H-like)	3.9	196	RAL/NRL	35	Ge 22+ (Ne-like)	8.6
65.8	LLNL	10	Eu 35+ (Ni-like)	2.1	196	NRC	36	Ge 22+ (Ne-like)	2.8
71	LLNL	10	Eu 35+ (Ni-like)	3.8	196	LLE	37	Ge 22+ (Ne-like)	2.3
80	ILE	26	Fl 9+ (H-like)	2.6	196	NRL	4	Ge 22+ (Ne-like)	4.7
81	RAL	26	F 8+ (H-like)	2.2	206	LLNL	10	Se 24+ (Ne-like)	16.0
99	LLNL	31	Ag 37+ (Ne-like)	10.1	206	NRL	80	Se 24+ (Ne-like)	5.9
99	CEA	74	Ag 37+ (Ni-like)	4.4	209	LLNL	10	Se 24+ (Ne-like)	15 2
100	LLNL	31	Ag 37+ (Ne-like)	6.1	209	NRL	80	Se 24+ (Ne-like)	5.9
102	ILE	26	O 8+ (H-like)	3.0	212	NRL	80	Zn 20+ (Ne-like)	3.5
105	LULI	21	Al 10+ (Li-like)	3.0	220	LLNL	10	Se 24+ (Ne-like)	9.2
105	ILE	26	Al 10+ (Li-like)	2.0	221	NRL	4	Cu 19+ (Ne-like)	3.0
105	LLE	75	Al 13+ (Li-like)	2.1	222	NRL	80	As 23+ (Ne-like)	8.1
106	RAL	76	Al 10+ (Li-like)	2.0	232	NRC	36	Ge 22+ (Ne-like)	5.0
106	LLNL	10	Mo 32+ (Ne-like)	3.8	232	LLE	37	Ge 22+ (Ne-like)	5.5
129	PPPL	22	Si 11+ (Li-like)	2.0	232	NRL	4	Ge 22+ (Ne-like)	6.2
131	LLNL	10	Mo 32+ (Ne-like)	7.1	236	RAL/NRL	35	Ge 22+ (Ne-like)	12.2
133	LLNL	10	Mo 32+ (Ne-like)	7.3	236	NRC	36	Ge 22+ (Ne-like)	5.0
139	LLNL	10	Mo 32+ (Ne-like)	5.0	236	LLE	37	Ge 22+ (Ne-like)	5.5
150	LLE	75	Al 10+ (Li-like)	2.7	236	NRL	80	Ge 22+ (Ne-like)	6.2
154	PPPL	22	Al 10+ (Li-like)	4.0	247	NRC	36	Ge 22+ (Ne-like)	3.6
154	RAL/LSAI	77	Al 10+ (Li-like)	3.3	247	LLE	37	Ge 22+ (Ne-like)	2.2
154	LLE	75	Al 10+ (Li-like)	2.5	262	LLNL	10	Se 24+ (Ne-like)	11.8
155	LLNL	10	Y 29+ (Ne-like)	11.0	262	NRL	80	Zn 20+ (Ne-like)	3.0
157	LLNL	10	Y 29+ (Ne-like)	11.0	267	NRL	80	Zn 20+ (Ne-like)	3.0
164	LLNL/CEL	78	Sr 28+ (Ne-like)	9.7	279	NRL	4	Cu 19+ (Ne-like)	2.6
165	LLNL/CEL	78	Sr 28+ (Ne-like)	8.8	284	NRL	4	Cu 19+ (Ne-like)	2.6
182	PPPL	20	C 5+ (H-like)	8.0	286	NRC	36	Ge 22+ (Ne-like)	2.4
182	PPPL	6	C 5+ (H-like)	2.4	286	LLE	37	Ge 22+ (Ne-like)	4.0
182	PPPL	25	C 5+ (H-like)	3.4	326	LLE/LLNL	40	Ti 12+ (Ne-like)	5.9
182	RAL	79	C 5+ (H-like)	3.9					

Key to Institutions:

C E L	Centre d'Etudes de Limeil-Valenton, Villeneuve St. Georges, France
I L E	Institute of Laser Engineering, Osaka University, Japan
L L E	Laboratory for Laser Engineering, Univ. of Rochester, Rochester,N Y
L L N L	Lawrence Livermore National Laboratory, Livermore, Ca.
L S A I	Laboratorie de Spectroscopie Atomique et Ionique, Orsay, France
L U L I	National Facility for Use of Intense Lasers, Palaiseau, France
N R C	National Research Council of Canada, Ottawa, Canada
N R L	Naval Research Laboratory, Washington, D C
P P P L	Princeton Plasma Physics Laboratory, Princeton, N J
R A L	Rutherford Appleton Laboratory, Didcot, Oxon, England

Historical Perspective

Lasers		X-ray Lasers
Ruby Laser HeNe Laser Application to retina repair First holograms	*1960*	•Recombination x-ray laser proposed.
Fiber Optics Laser Surgery Laser Video Disk	*1970*	•Population inversion demonstrated. •Ne-like scheme proposed.
Bar Code Scanners Laser Printers	*1980*	•Normal incidence soft x-ray mirrors. •Lasing demonstrated at 182Å and 206,209Å •Application to microscopy and holography
Optical Computer	*1990*	*Future :* • *Cavity operation* • *'Personal' x-ray lasers* • *Lithographic inspection* • *Nonlinear x-ray optics* • *Medical diagnostics* • *? ? ?*
	2000	

Fig. 1

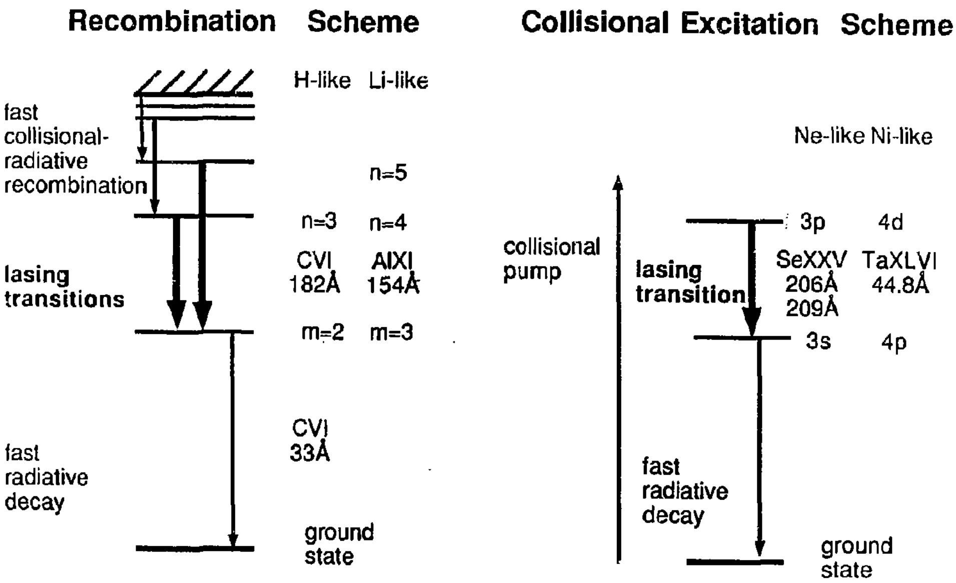
Recombination Scheme
H-like Li-like
fast collisional-radiative recombination
n=5
n=3 n=4
lasing transitions
CVI 182Å
AlXI 154Å
m=2 m=3
CVI 33Å
fast radiative decay
ground state
Collisional Excitation Scheme
Ne-like Ni-like
collisional pump
3p 4d
lasing transition
SeXXV 206Å 209Å
TaXLVI 44.8Å
3s 4p
fast radiative decay
ground state

Fig 2

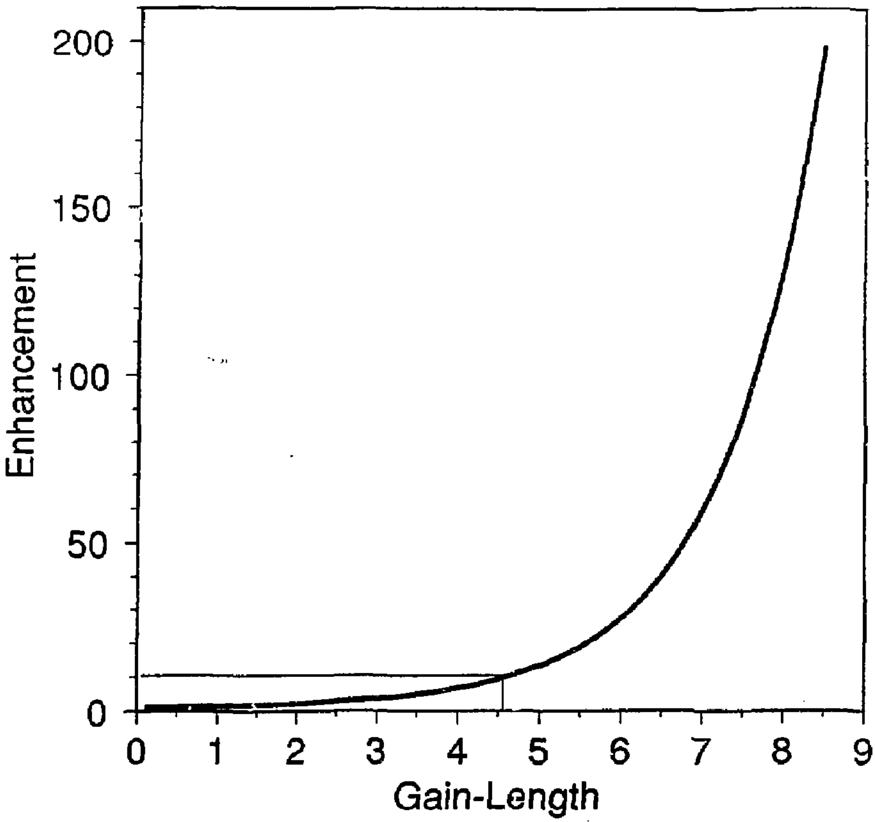

Fig. 3

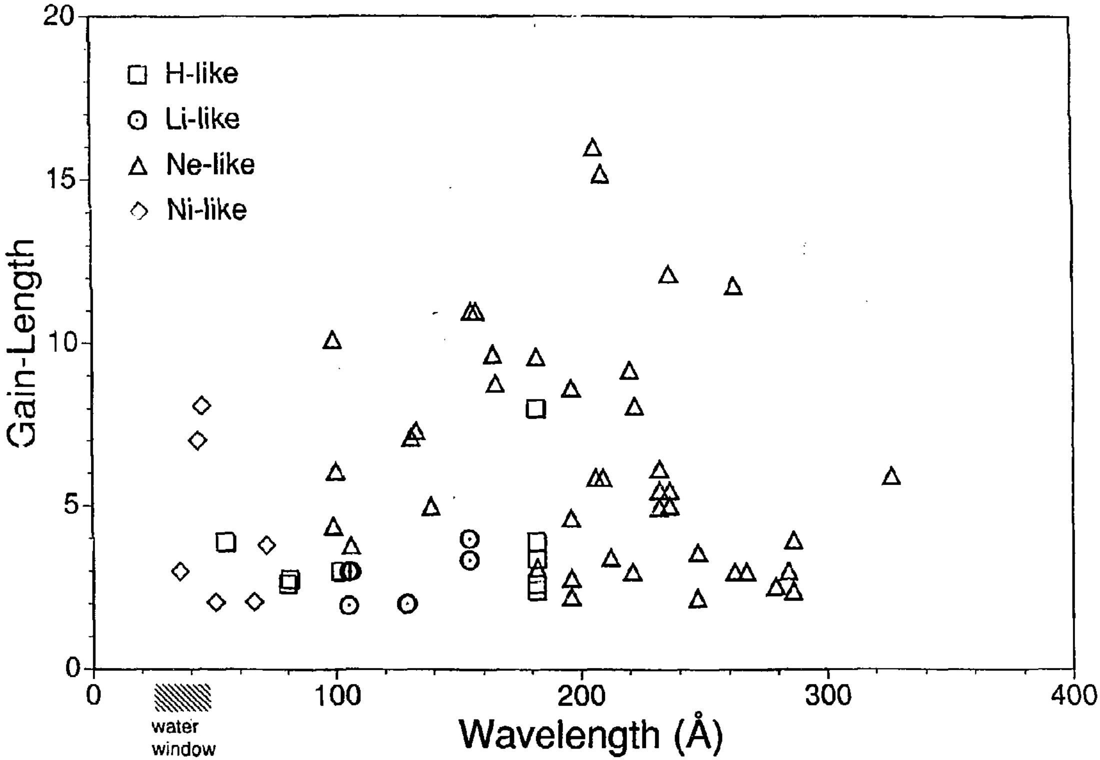
H-like
Li-like
Ne-like
Ni-like
Gain-Length
20
15
10
5
0
0
100
200
300
400
water
window
Wavelength (Å)

Fig. 4

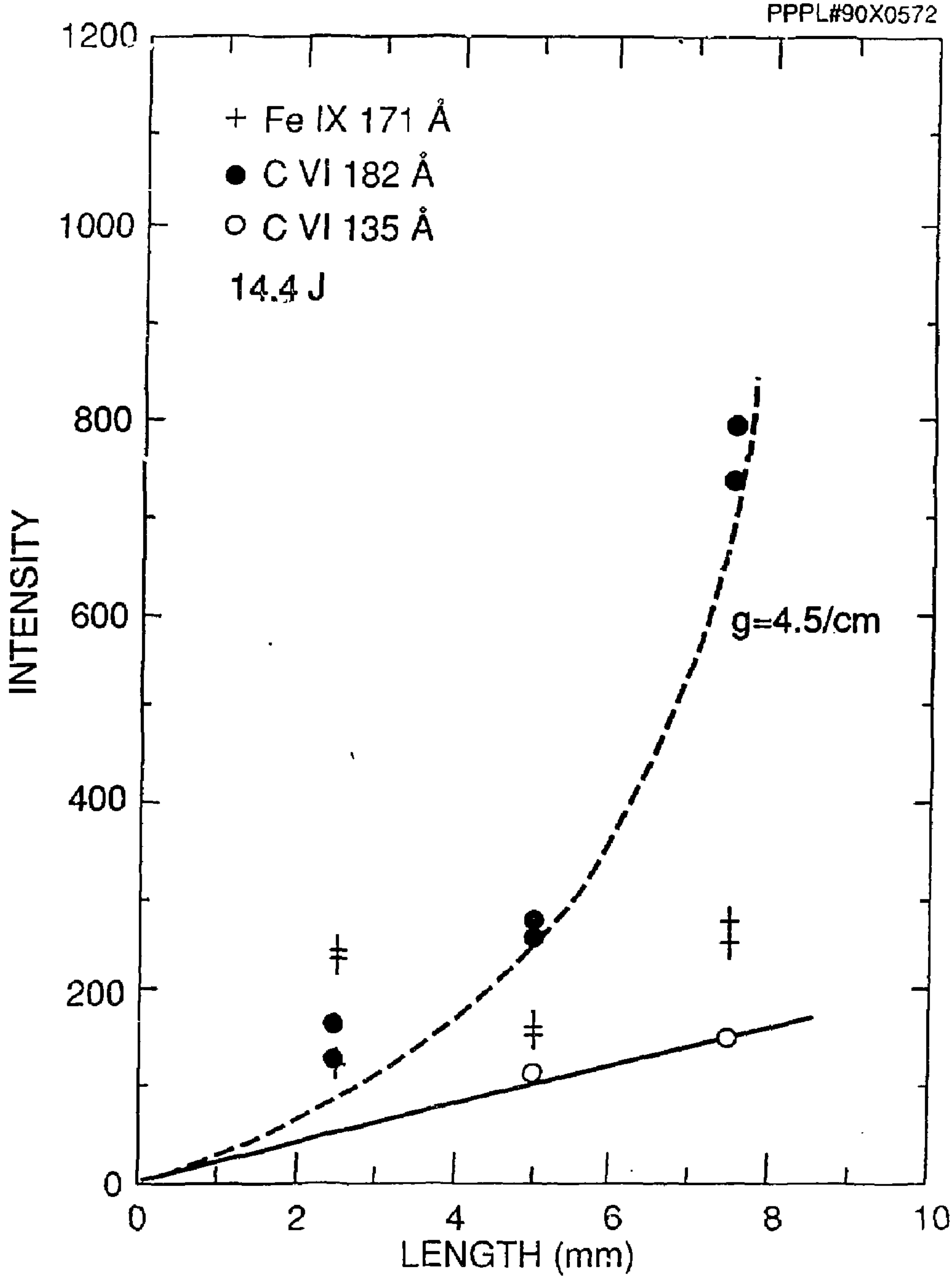
PPPL#90X0572
+ Fe IX 171 Å
● C VI 182 Å
○ C VI 135 Å
14.4 J
g=4.5/cm
INTENSITY
0
200
400
600
800
1000
1200
LENGTH (mm)
0
2
4
6
8
10

Fig. 5

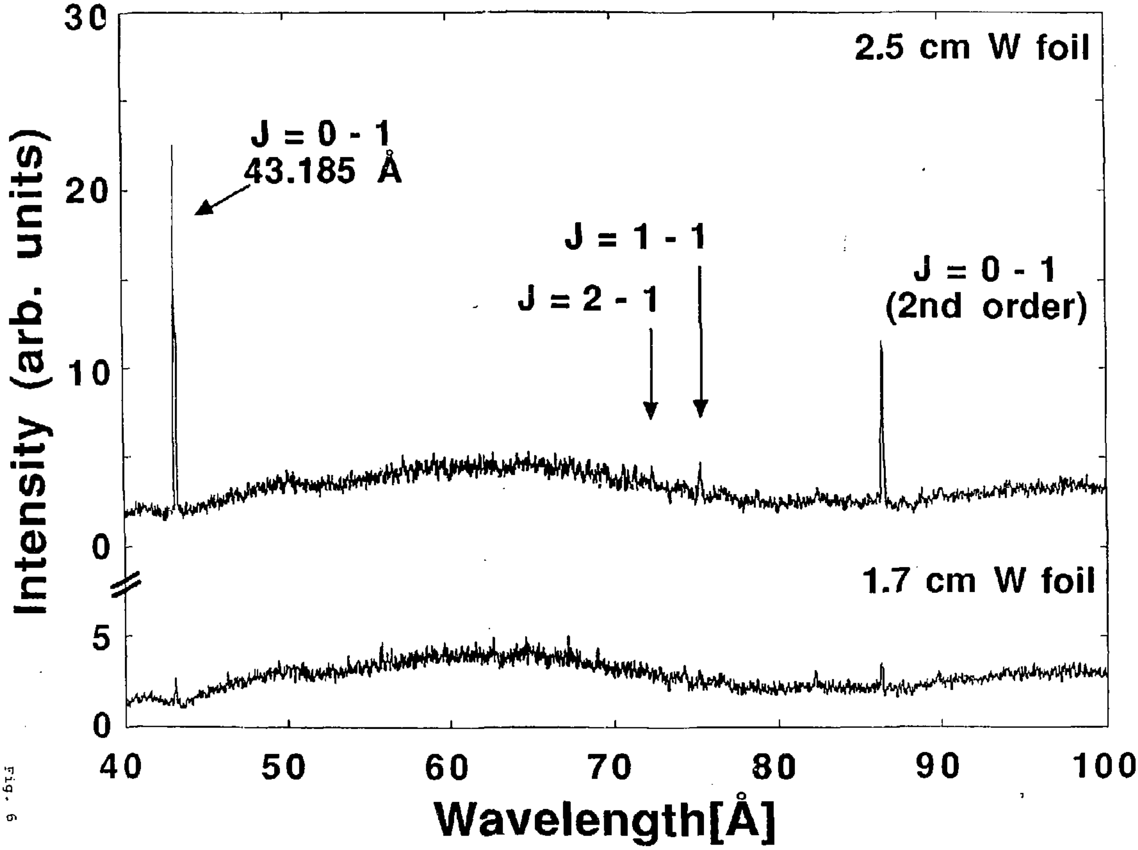
2.5 cm W foil
J = 0 - 1
43.185 Å
J = 1 - 1
J = 2 - 1
J = 0 - 1
(2nd order)
1.7 cm W foil
Intensity (arb. units)
30
20
10
0
5
0
40
50
60
70
80
90
100
Wavelength[Å]

Fig. 6

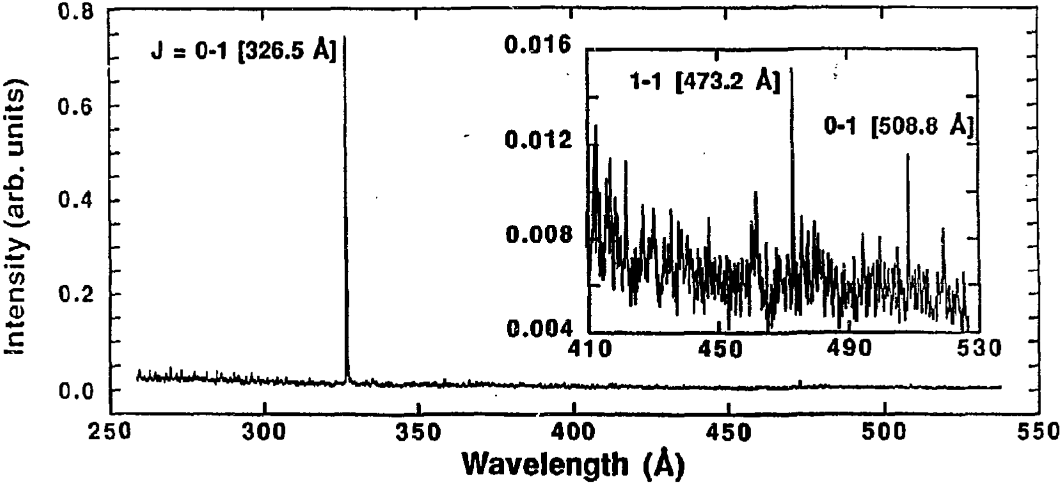
J = 0-1 [326.5 Å]
1-1 [473.2 Å]
0-1 [508.8 Å]
Intensity (arb. units)
0.0
0.2
0.4
0.6
0.8
Wavelength (Å)
250
300
350
400
450
500
550
0.004
0.008
0.012
0.016
410
450
490
530

Fig. 7

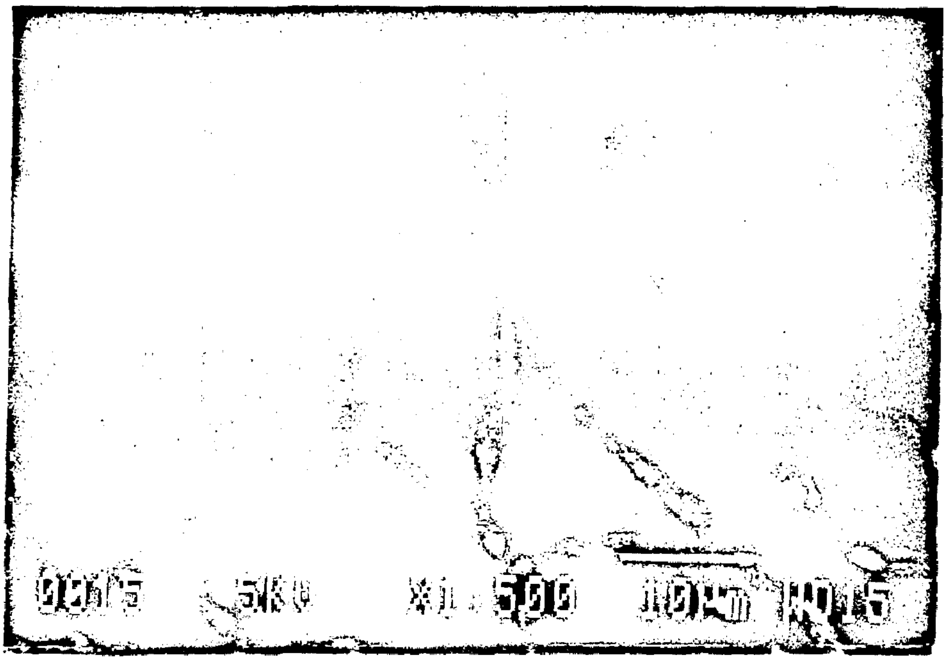

Fig. 8

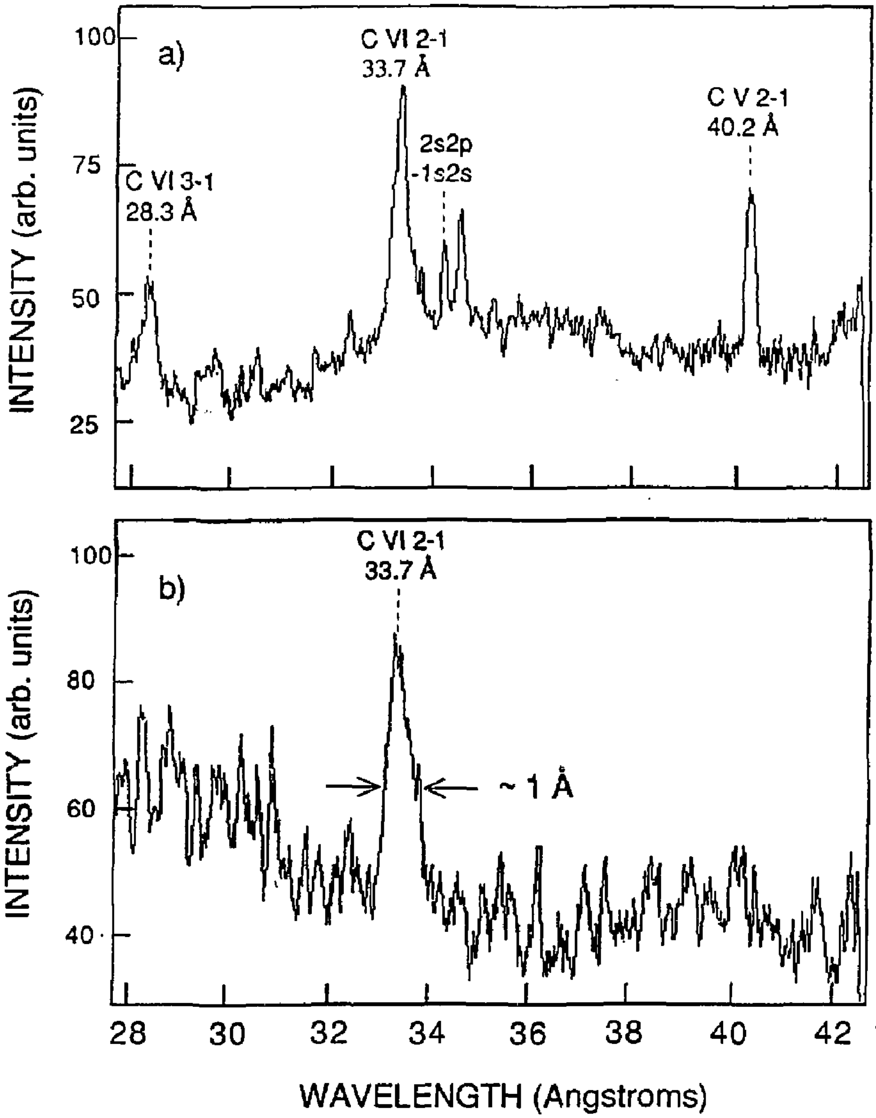
a)
C VI 2-1
33.7 Å
2s2p
-1s2s
C V 2-1
40.2 Å
C VI 3-1
28.3 Å
b)
C VI 2-1
33.7 Å
~ 1 Å
INTENSITY (arb. units)
100
75
50
25
80
60
40
28
30
32
34
36
38
40
42
WAVELENGTH (Angstroms)

Fig. 9