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A review of X-ray laser development at Rutherford Appleton Laboratory

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Abstract

Recent experiments undertaken at the Rutherford Appleton Laboratory to produce X-ray lasing over the 5–30 nm wavelength range are reviewed. The efficiency of lasing is optimized when the main pumping pulse interacts with a preformed plasma. Experiments using double 75-ps pulses and picosecond pulses superimposed on 300-ps background pulses are described. The use of travelling wave pumping with the approximately picosecond pulse experiments is necessary as the gain duration becomes comparable to the time for the X-ray laser pulse to propagate along the target length. Results from a model taking account of laser saturation and deviations from the speed of light c of the travelling wave and X-ray laser group velocity are presented. We show that X-ray laser pulses as short as 2–3 ps can be produced with optical pumping pulses of $\approx$1-ps.

Keywords: Laser; Plasma; Saturation; X-ray

1. INTRODUCTION

Experiments at the Rutherford Appleton Laboratory (RAL) and elsewhere have shown that soft X-ray lasers can be driven into saturation by short pulse length optical lasers irradiating slab targets. Saturated lasing occurs when stimulated emission causes more than half of the depopulation of the upper lasing level. Saturation is an important milestone for any new lasing scheme as the laser efficiency is optimized, shot-to-shot variability decreases, the laser output is high, and the beam quality generally improves.

Saturated lasing has been achieved at wavelengths as short as 5.9 nm (Smith *et al.*, 1999) in experiments at the RAL with double pulses of 75-ps duration irradiating dysprosium slab targets. An important step in achieving such short wavelength saturated lasing was the discovery that the efficiency of lasing increases if a prepulse is used and the main pumping pulse producing the X-ray lasing interacts with a long-scalelength preplasma. Simulations show (Behjat *et al.*, 1997; Lin *et al.*, 1998*a*) that, compared to direct irradiation of a solid target with the main pumping laser pulse, using a preplasma produces better propagation of the X-ray laser pulse along the target length. Refraction is reduced as the density gradients are less and the volume of plasma exhibiting gain is larger. In addition, the main pumping pulse irradiation is better absorbed (Tagviashvili & Tallents, 1998).

Recently, it has been shown that the necessary driver laser energy for X-ray lasing can be reduced further by using approximately picosecond pulses produced by lasers operating with chirped pulse amplification (CPA) (Warwick *et al.*, 1998; Lin *et al.*, 1999). Again, a prepulse plasma is formed. At RAL, the prepulse plasma is created by irradiation with a pulse of 300 ps arising from the stretched, but uncompressed pulse used for the CPA beam. Using short approximately picosecond pulses offers the opportunity to achieve X-ray lasing with table-top lasers. Laser energies as low as 7 J have been used to produce X-ray lasing at wavelengths as short as 14 nm (Dunn *et al.*, 2000).

Saturated X-ray lasing has been produced in ions where the first two or three shells are occupied with electrons in the ground state. The ions are iso-electronic to neon or nickel, respectively. Monopole collisional excitation from the ground state to the $3p$ or $4d$ levels produces a population inversion with respect to $2s$ or $3p$ levels (for, respectively, Ne-like and

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Ni-like ions). The 2*s* and 3*p* levels can radiatively decay rapidly to the respective ground states, while the upper 3*p* and 4*d* lasing levels are forbidden to have radiative transitions to the ground and so are metastable. Nickel-like ions have a larger quantum efficiency (i.e., the ratio of the lasing levels energy difference to the energy of the upper lasing level above ground). Consequently, Ni-like ions have produced lasing at shorter wavelengths.

In all X-ray laser experiments, a line of plasma needs to be formed along which the X-ray laser can propagate and amplify. In laser-pumped experiments, the driving laser is focused in a line onto the target. At RAL, the line focus is produced using spherical mirrors tilted off-axis (Ross *et al.*, 1987). With approximately picosecond pulses, the laser gain duration is short and becomes comparable or shorter than the time for X-ray laser pulses to propagate the length of the target. To optimize the efficiency of pumping, it is necessary to tilt the irradiating pulsefront so that a travelling wave pumping along the target is achieved. With travelling wave pumping, the gain is produced as the X-ray pulse travels along the target. At RAL, there is an intrinsic travelling wave velocity of 2.5–3 c (where c is the speed of light in vacuum) due to the aspheric mirror tilt used to produce the line focus. An additional grating is employed in the driving laser beamline to tilt the energy pulse front to achieve a travelling wave at c (Collier *et al.*, 1997).

2. X-RAY LASER PROPERTIES

The far-field beam profile produced by X-ray lasers has been routinely measured at RAL using multilayer mirror optics to focus the X-ray laser output onto CCD detectors (Fig. 1). The far-field beam profile is typically crescent shaped with a smaller horizontal divergence in the plane parallel to the target normal compared to the vertical direction parallel to the target surface. The reduced horizontal divergence arises because of the small effect of refraction on the X-ray laser beam in that direction due to double pulsing. However, some refraction does occur because the X-ray beam is directed at an angle to the target (e.g., ≈15 mrad in Fig. 1). There are normally no special techniques used to control the vertical divergence of X-ray lasers and so refraction occurs due to electron density gradients arising from the finite width of the line focus. Simulations using a fluid and atomic physics code EHYBRID to calculate the gain and electron density profiles and a ray tracing code to evaluate the propagation of the X-ray laser beam along the target length produce X-ray laser beam footprints in good agreement with the measured profiles (see Fig. 1b).

Following a simulation study (Simms & Pert, 1997), an experiment was undertaken at RAL to produce an inward (toward the target) bend of density contours which could act to focus the X-ray laser beam in the vertical direction and essentially produce a one-dimensional waveguide. The main pumping pulse was more tightly focused here than the prepulse, so that a “density well” was produced running along the length of the target due to the extra heating in the center of the preplasma. An initial experiment produced a density well in a short 2–4 mm length of target. The well was illuminated with the Ne-like Ge X-ray laser output at 19.6 nm from a 40-mm length of Ge in a direction approximately parallel to the short length target. The density well

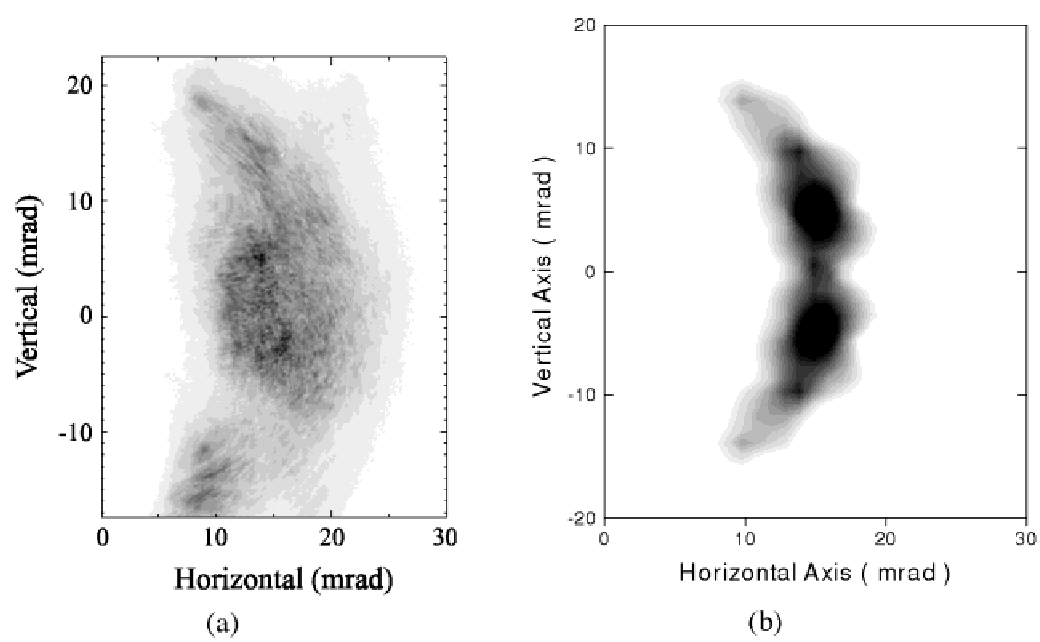
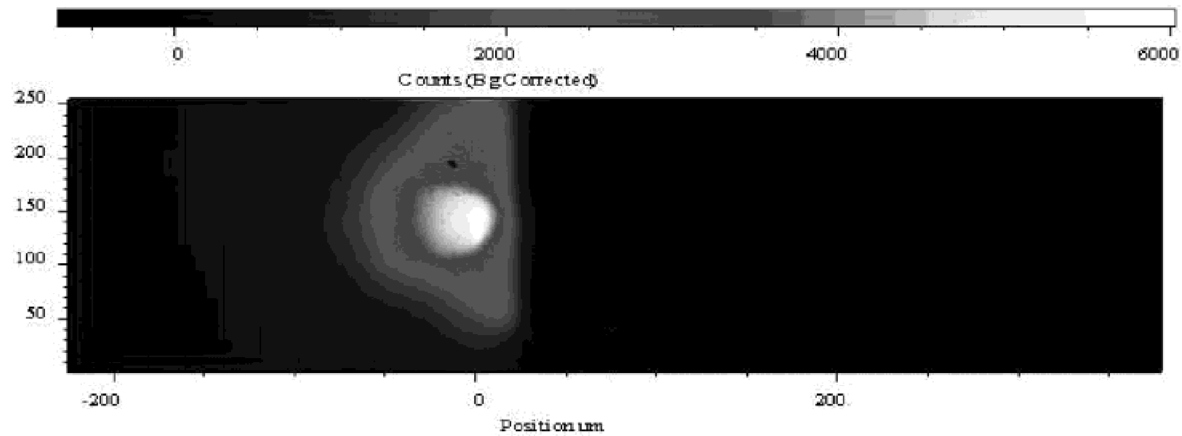
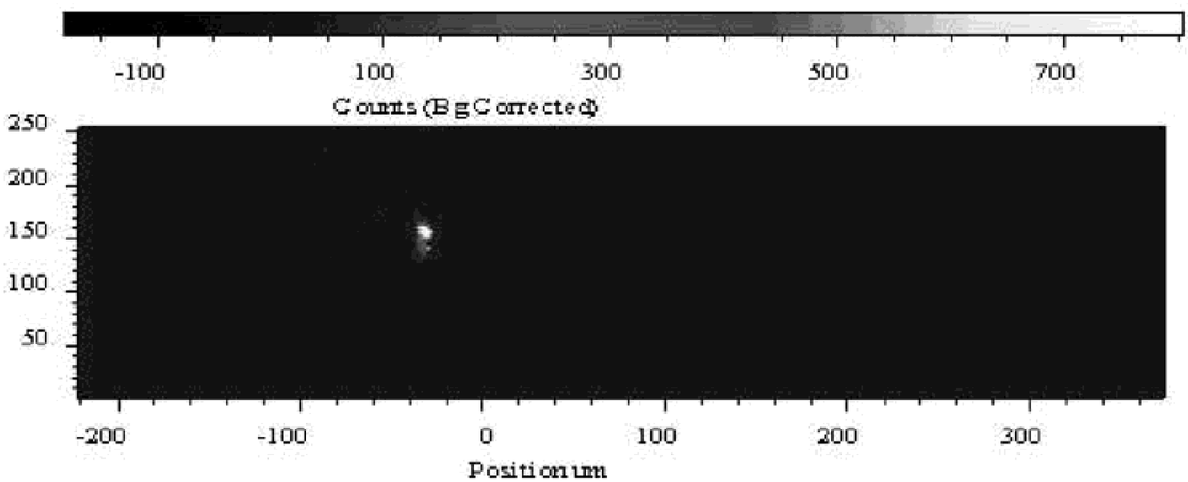


Fig. 1. The far-field Ne-like Ge X-ray laser output at 19.6 nm produced with double 75-ps optical pulses (a) measured with an imaging multilayer mirror and CCD and (b) simulated using the EHYBRID and ray trace codes.



(a)



(b)

Fig. 2. Beam profiles of a Ne-like Ge laser at 19.6 nm at a distance of 1.6 cm from a 4-mm length of density well target of (a) copper and (b) germanium. The profile after passing through the germanium is spatially smaller, but much less intense. The relative but comparable intensity scales are indicated above the respective plots (light shading is more intense).

was produced in a copper plasma and in a germanium plasma. Far-field beam profiles showed that the density well acted similarly to a pinhole in improving the quality of the X-ray laser beam, but additional amplification in the germanium density well did not occur (Fig. 2). Indeed the germanium well attenuated the X-ray laser beam by a much greater amount than the copper well.

The gain of X-ray laser media is usually measured by varying the length of the target. At shorter lengths where saturation is not occuring, the approximately exponential increase of X-ray laser output with length can be fitted to measure the gain coefficient (Fig. 3). This is commonly done using an approximate formula taking account of averaging over the line spectral profile as initially introduced by Linford *et al.* (1974). With saturation at longer lengths, a more complete model of amplified spontaneous emission (ASE) taking account of gain, the spectral line width, and

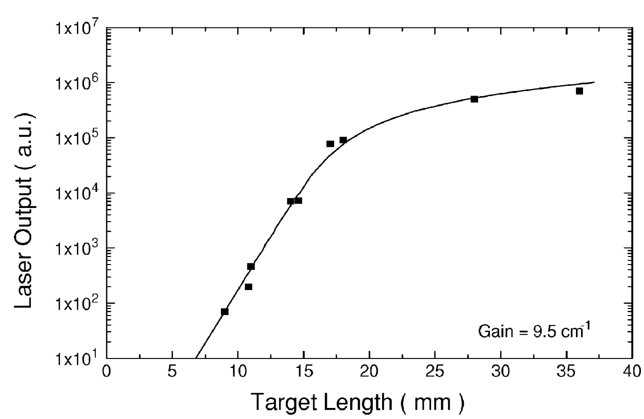


Fig. 3. The variation with length of the output of Ni-like Sm at 7.3 nm pumped with double 75-ps pulses. The gain coefficient of 9.5 cm^{-1} is obtained by fitting the Linford formula to the approximately exponential increase in output at shorter target lengths.

gain saturation needs to be used (Lin *et al.*, 1998*b*; Pert, 1994). The more complete model is used to fit the solid curve to the data points of Figure 3.

Interestingly, the Ni-like X-ray lasers exhibit gain on two $J = 0 - 1$ transitions emanating from the same upper quantum state. Atomic physics modeling (Daido *et al.*, 1995) shows that the gains for the two $J = 0 - 1$ lasing transitions are close to equal for Gd with atomic number $Z = 64$, but become increasingly unequal for both lower and higher Z with increasing distance of Z away from 64. Ni-like Dy ($Z = 66$) lasing was investigated at RAL and produced the current shortest wavelength saturated lasing output at 5.9 nm (Smith *et al.*, 1999). The lower gain line at 6.4 nm reduces in output with increasing target length as the higher gain line is driven further into saturation (Fig. 4). Extending the ASE model to include both lasing lines produces good model fits to the experimental data points (see Fig. 4 and the discussion in Smith *et al.*, 1999).

There is evidence for a degree of coherence over the X-ray laser beam profiles (Burge *et al.*, 1998). For example, splitting X-ray laser beams with a transmission grating or Lloyd's mirror and subsequently recombining the beams using a multilayer mirror produces interference fringes of low (~0.1) visibility (Topping *et al.*, 2000). However, the visibility is probably dominated by the mismatch in beam intensity rather than phase in the combined beams. Balancing the local beam intensity at recombination should produce much greater fringe visibility.

Experiments have failed to measure preferred polarizations in X-ray laser beams produced by amplified spontaneous emission (Rus *et al.*, 1995). Indeed, the expected times for collisions to randomize the orientation of ions in the plasma is sufficiently small that a preferred polarization should not occur (Sureau & Holden, 1995).

The spectral bandwidth of X-ray lasers is very narrow (Koch *et al.*, 1994). The gain bandwidth due largely to thermal Doppler broadening arising from the temperature of the ions is typically such that $\nu/\Delta\nu \sim 20{,}000$. With amplification, the output X-ray laser pulse can be expected to have $\nu/\Delta\nu > 50{,}000$.

3. EXTENDING X-RAY LASERS WITH PICOSECOND PUMPING

The production of picosecond optical laser pulses has required the development of CPA technology (Ross *et al.*, 1997). Such picosecond lasers are used for many high irradiance experiments and have produced much novel physics. X-ray lasing with approximate picosecond pumping is potentially more efficient, as overionization beyond the desired Ne- or Ni-like stage associated with longer duration pumping can be reduced (McCabe & Pert, 2000). The monopole excitation to produce the population inversion can proceed rapidly with the onset of the pumping pulse, but there is insufficient time for the ground-state populations of the lasing ions to be severely depleted by ionization. Resonance line spectra measured transversely to the line focus show the reduced "overionization" achieved with approximately picosecond pumping compared to 75-ps pulse pumping (Fig. 5). The approximately picosecond pumping spectra show much weaker emission from F-like Ge ions compared to the

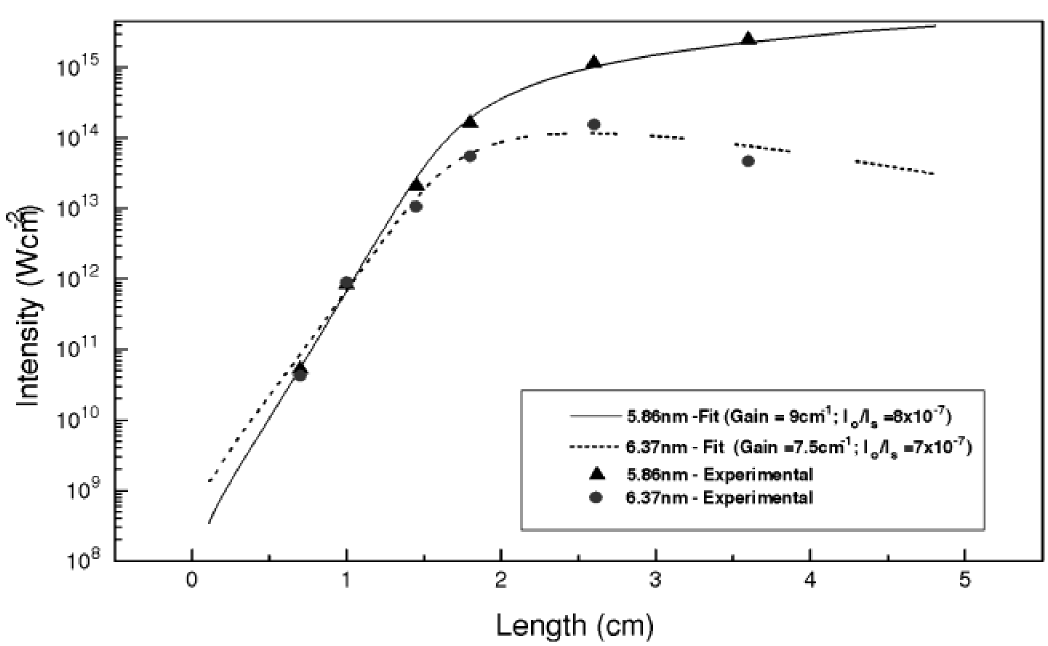


Fig. 4. The variation with length of the Ni-like dysprosium output at 6.4 nm (lower gain) and 5.9 nm (higher gain). Model fits to the experimental data are fitted as curves. The laser pumping comprises two 75-ps duration pulses.

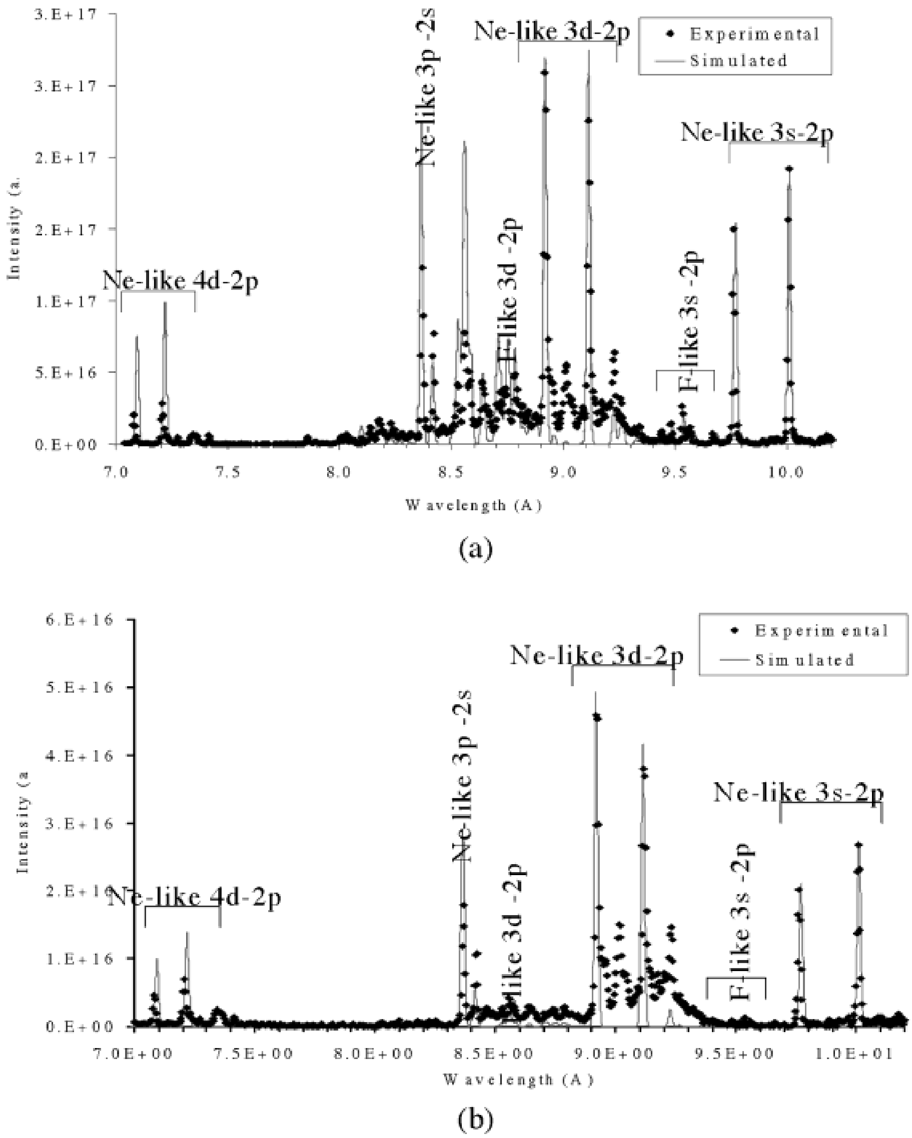


Fig. 5. Resonance line spectra of Ne-like Ge pumped by (a) two 75-ps pulses and (b) an approximate picosecond pulse superimposed on a 300-ps background pulse.

75-ps spectra. Modeling of the spectra using the EHYBRID code shows general agreement with the measured spectra (Pestehe & Tallents, 2002).

Simulations show that with approximately picosecond pumping lasers, the gain duration is ~30–40 ps for Ne-like ions (King *et al.*, 2001) and 10–20 ps for Ni-like ions (G. Pert, in prep.). As the X-ray laser pulse travels at a maximum of c in the plasma (corresponding to a time of 33 ps/cm), this can result in a mismatch between the propagating X-ray laser pulse and the onset of gain. Travelling wave pumping is employed to ensure that the X-ray pulse and the gain onset coincide. Experiments show that it is important to match the travelling wave velocity to c to ensure the optimum X-ray laser output (King *et al.*, 2001) (Fig. 6).

With high gain, the group velocity of the X-ray pulse may drop below c and a mismatch between X-ray laser pulse and gain can then occur even with travelling wave pumping at c. Group velocity and travelling wave velocity mismatch effects have been examined in a model developed by Strati and Tallents (1999, 2001). It is shown that the optimum travelling wave velocity can be less than c (Fig. 7), but the effect on the output intensities of the X-ray laser beam is not very large if there is only a small mismatch between the group velocity and travelling wave velocity. The model shows that the output duration of the X-ray laser is significantly reduced compared to the gain duration. For example, it should be possible to produce lasing pulses of 1.4 ps when the gain duration is 20 ps

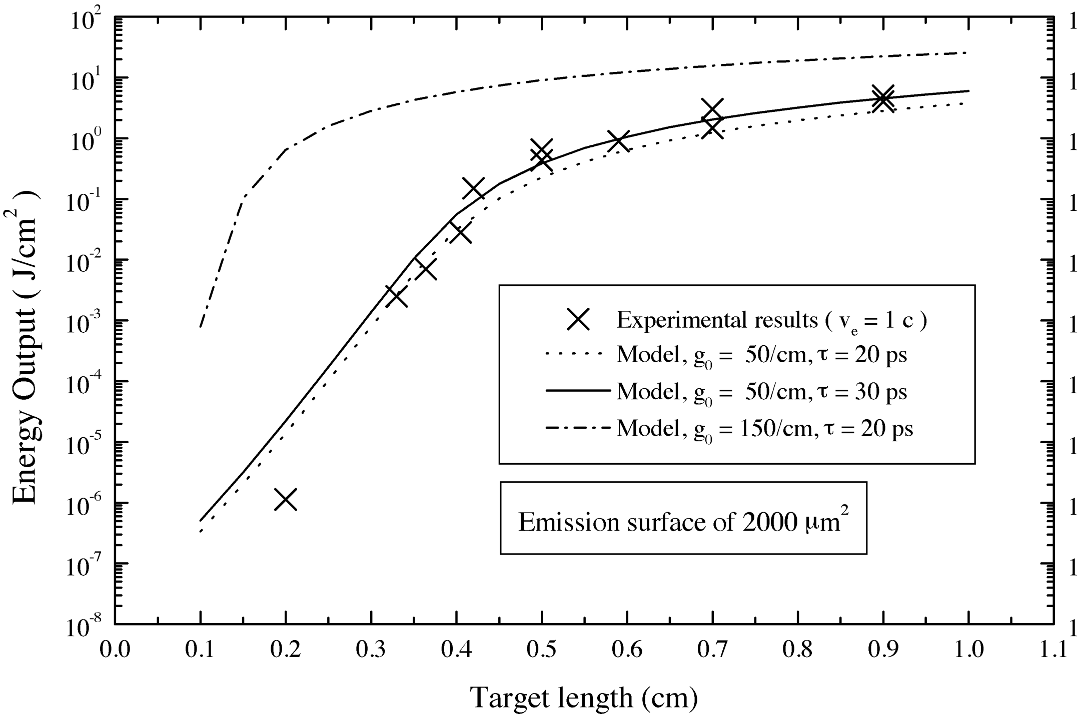


Fig. 6. X-ray laser output at 19.6 nm for Ne-like Ge pumped with approximate picosecond pulses and travelling wave excitation along the target length. Model results with the parameters shown are also plotted as curves.

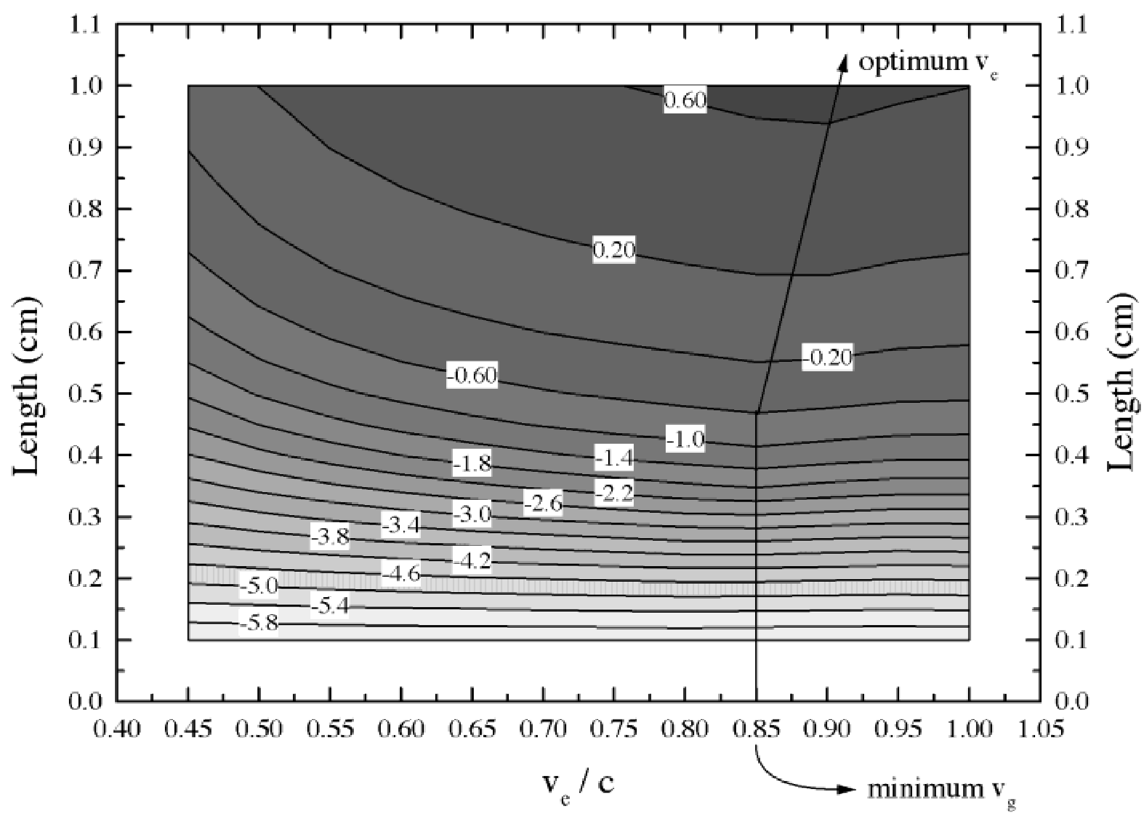


Fig. 7. X-ray laser output in units of Jcm^{-2} plotted as contours on a base10 logarithmic scale as a function of target length and excitation speed along the target. The calculations are for gain coefficient 50 cm^{-1}, gain duration 20 ps, spectral bandwidth $\sim\nu/\Delta\nu = 10^4$, saturation flux 2×10^{10} Wcm^{-2} and "spontaneous emission" of 2×10^3 Wcm^{-2}.

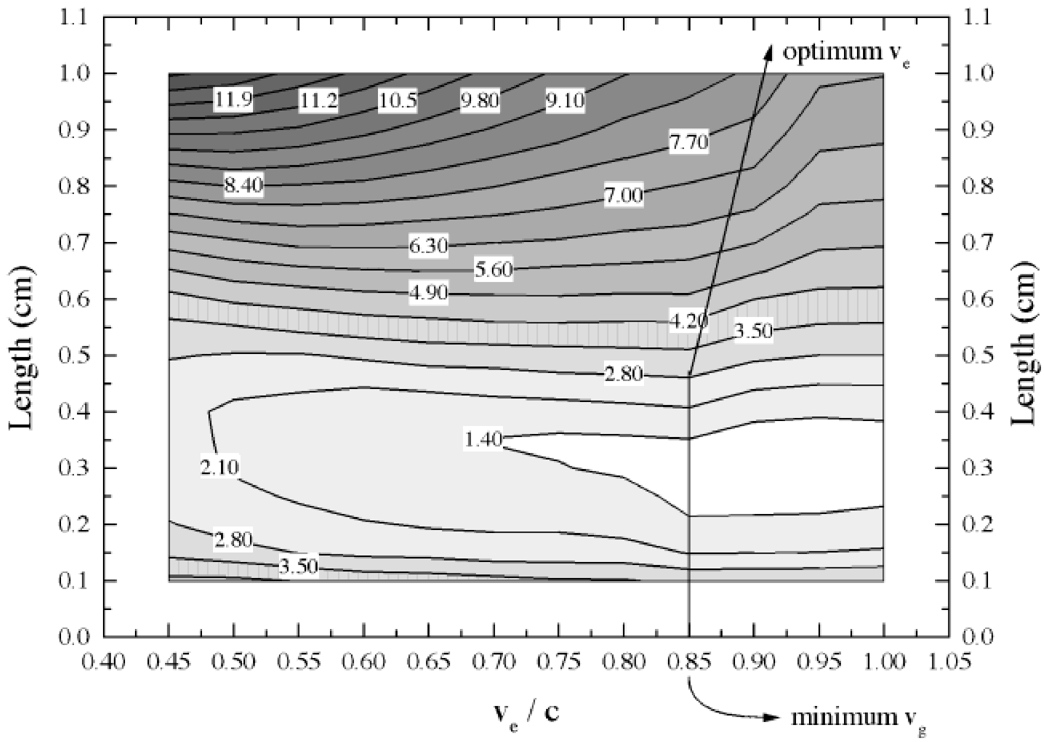


Fig. 8. Contours of pulse duration in picosecond for the conditions of Figure 7.

(Fig. 8). A short duration of lasing ∼2–3 ps for Ni-like Ag has been measured with a fast streak camera (see Fig. 9 and Klisnick *et al.*, 2002). In Figure 9, the temporal resolution of the streak camera and spectrometer is estimated to be ∼1 ps. The X-ray laser output is spectrally resolved with a flat field spectrometer and filtered with 1.2 μm of CH to ensure that the streak camera is operated below saturation.

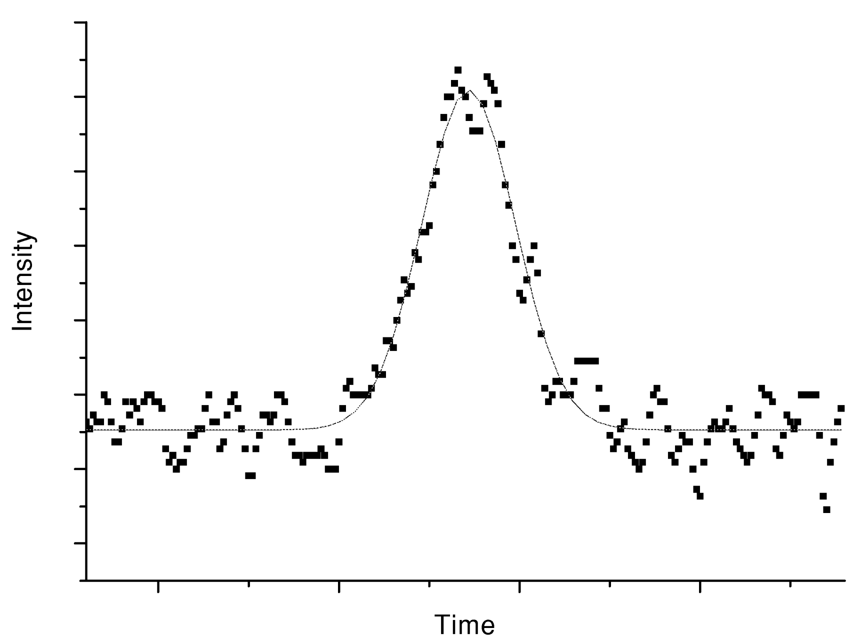


Fig. 9. Line-out of streak camera output of the Ni-like Ag X-ray laser line at 14 nm with a Gaussian fitted curve of temporal half-width 3 ps. The X-ray laser was pumped with 12 J in a 300-ps background pulse and 24 J in a 1-ps duration pulse incident 200 ps after the peak of the background pulse onto a 10-mm-long target.

4. DIRECTIONS OF LASER-PUMPED X-RAY LASERS

It is possible that other transitions my produce shorter wavelength lasing in the Ne- or Ni-like ions. The lasing transitions observed so far occur in ions where the excited electron has vacated a $2p$ (Ne-like) or $3d$ (Ni-like) sublevel of the ground state. Higher quantum efficiency and shorter wavelength lasing could occur where the excited electron vacates a $2s$ (Ne-like) or $3p$ (Ni-like) sublevel (see, e.g., Fig. 10 for Ne-like Ge). Excited ions of Ne-like Ge with $2s$ sublevel holes are readily produced as $3p$–$2s$ transitions to the ground are observed (see Fig. 5). However, detailed simulations with the EHYBRID code show that the gain coefficients for the Ne-like Ge "inner shell" lasing transitions are approximately an order of magnitude less than the gain coefficients for the observed lasing lines. The inner shell lasing transitions are also more affected by refraction, as they tend to occur at higher electron density with a narrower region of gain (S.J. Pestehe *et al.*, in prep.).

X-ray lasers have been employed to record imprinting of the Rayleigh–Taylor instability in laser-driven foils and to measure the opacity of low temperature, high density plasmas at X-ray laser wavelengths (Kalantar *et al.*, 1997; Wolfrum *et al.*, 1998). There is a useful niche here for X-ray lasers as they are bright and can produce a measurable signal above background levels with strong attenuation (Eker, 2000; see also Tallents *et al.*, 1999). As X-ray lasers can be focused with intensity comparable to their saturation intensity ($\sim 10^{10}$–10^{11} Wcm^{-2}), they should be useful for applications requiring a high flux such as in nonlinear optics experiments (Topping *et al.*, 2000) and as a source for Thomson scatter from plasmas. The narrow spectral bandwidth (such that $\nu/\Delta\nu > 50{,}000$) cannot be produced at comparable wavelengths with other sources. X-ray lasers pumped with optical lasers are currently the brightest, narrow band laboratory sources in the extreme ultraviolet ($\sim$5–30 nm) with peak photon fluxes of $\sim 10^{24}$ photons s^{-1} mm^{-1} mrad^{-1}.

5. CONCLUSIONS

Recent X-ray laser development at the Rutherford Appleton Laboratory has been reviewed. Pumping the X-ray lasers with optical laser pulses incident into plasmas preformed with prepulses has been shown to reduce refraction effects on the X-ray laser propagation and to lead to greater pumping efficiency. Some experiments to reduce refraction effects in the direction parallel to the target surface by the creation of a density well to act as a one-dimensional waveguide to the X-ray laser pulse have been briefly described. The pumping of X-ray lasers with approximately picosecond pulses has been outlined. Difficulties due to mismatches between the travelling wave and X-ray laser group velocity have been taken into account using a self-consistent model. We have shown that X-ray laser pulses as short as 2–3 ps can be produced with optical pumping pulses of $\approx$1 ps.

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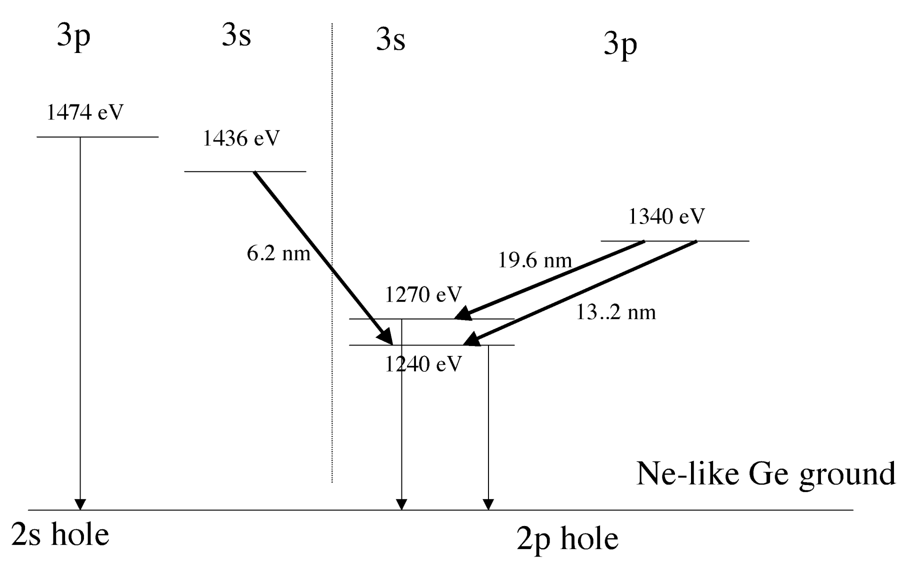

Fig. 10. Grotrian diagram showing the $n = 2$ ground state and some of the $n = 3$ subshell structure of Ne-like Ge. The vertical broken line divides subshells with $2s$ or $2p$ holes.

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