Technical Report

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Optimisation of Transient Gain X-ray Laser for 20-32 nm

TMR Large-Scale Facilities Access Programme

PV Nickles et al

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SUMMARY

This report describes the experiment entitled 'Optimisation of Transient Gain X-ray Laser for 20-32 nm'; carried out at the Central Laser Facility (CLF) from the 26th August to the 6th October 1997. The experiment, funded by the Framework IV Large-Scale Facilities Access Scheme, was proposed by Dr P.V. Nickles, Max-Born-Institut, Rudower Chaussee 6, D-12489 Berlin, Germany and carried out by visiting researchers from the Institute. They were supported by UK researchers from the University of Oxford, University of Essex, Queens University Belfast, University of York and The Central Laser Facility, Rutherford Appleton Laboratory.

Experimental Results

- Results obtained show for the first time that the new transient gain excitation scheme can be brought into saturation on the 3p-3s line in Ti at 32.6 nm (and very high gain for the 3p-3s line at) as well.
- Measurable amplified emission was observed from 3 mm targets for a total pump energy of 0.5 J, representing a truly table-top system. This is 1- 2 orders of magnitude in pump energy reduction as compared to common quasistationary XRL systems.
- With less than 30 Joules of energy incident on a 5 mm Ge target we have achieved a gain coefficient of 30 cm^{-1} and a gain-length product of 15, which is approaching the saturation limit of this laser. This gain coefficient is the highest ever observed in Ne-like Ge and demonstrates the effectiveness and efficiency of the transient excitation scheme.
- Reliable X-ray lasing has been demonstrated utilising a novel excitation scheme which requires exceptionally low input pump energies. This should also be attractive for future nickel like and innershell transitions, opening a route to yet shorter wavelength low sized X-ray lasers.

The CLF makes beam time at its facilities available to European Researchers with funding from DG-XII, CEC under the Large Facilities Access Scheme. For further information contact Dr. Chris Edwards at the CLF. Tel: (0)1235 445582, e-mail: c.b.edwards@rl.ac.uk

From left to right:

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Middle row: M Stainsby, E Wolfrum, M Schnürer, J Collier, J Warwick, A Demir, D Neely

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Publications Arising

Refereed Publications

M.P.Kalachnikov, P.V. Nickles, M. Schnürer, W.Sandner, V.N. Shlyaptsev, C. Danson, D. Neely, E. Wolfrum, J.Zhang, A.Behjat, A. Demir, G.J. Tallents, P.J. Warwick, C.L.S. Lewis. "Saturated operation of a transient collisional X-ray laser." Submitted to **Phys Rev A.**

PJ Warwick, A Behjat, A Demir, MP Kalachnikov, CLS Lewis, D Neely, PV Nickles M Schnürer, GJ Tallents E Wolfrum; Observation of high transient gain in the germanium X-ray laser at 19.6 nm **JOSA B** , submitted

Conference Proceedings

PV Nickles, MP Kalachnikov, M Schnürer, W Sandner, VN Shlyaptsev, C Danson, D Neely, E Wolfrum, J Zhang, A Behjat, A Demir, GJ Tallents, PJ Warwick, CLS Lewis; Transient inversion x-ray lasers in Ti and Ge SPIE Conf. Proceed. 3156, in press

Conference Presentations

International Conference on Superstrong Fields in Plasmas, Villa Monastero, Varenna, Italy, Aug 27 - Sept 2, 1997

C Danson, PV Nickles, A Behjat, J Collier, A Demir, MP Kalachnikov, M Key, C Lewis, D Neely, DA Pepler, GJ Pert, M Schnurer, W Sander, VN Shlyaptsev, G Tallents, J Warwick, E Wolfrum and J Zhang. "Implementation of a CPA Line Focus Travelling Wave for Efficient Saturated Lasing of Ne-Like Ti and Ge."

KA Janulewicz, SB Healy, GJ Pert, PV Nickles, M Schnuerer, M Kalachnikov, W Sander, J Warwick, CLS Lewis, C Danson, D Neely, E Wolfrum, J Zhang, A Behjat, A Demir and G Tallents. "Saturation in Transient-Gain Scheme of Collisionally Pumped X-ray Lasers."

SPIE International Symposium on Optical Science, Engineering and Instrumentation. San Diego Convention Center, San Diego, California, USA. 27 July - 1 August 1997.

P.V. Nickles, M. Schnürer, M.P.Kalachnikov, W.Sandner, V.N. Shlyaptsev, C. Danson, D. Neely, E. Wolfrum, A.Behjat, A. Demir, G.J. Tallents, P.J. Warwick and C.L.S. Lewis. "Transient Inversion XUV-lasers in Ti and Ge."

G.J. Tallents, A.Behjat, A. Demir, JY Lin, C.L.S. Lewis , AG MacPhee, SP McCabe, P.J. Warwick, D. Neely, E. Wolfrum, J.Zhang, GJ Pert, P.V. Nickles, M.P.Kalachnikov and M. Schnürer. "X-ray Enhancement with Multi-pulsing."

OSA Topical Meeting on the Applications of High Field and Short Wavelength Sources, Sante Fe, New Mexico, March 19-22, 1997

PV Nickles, MP Kalachnikov, M Schnurer, W Sander, VN Shlyaptsev, C Danson, D Neely, E Wolfrum, M Key, A Behjat, A Demir, G Tallents, GJ Pert, J Warwick and C Lewis. "A Short-long pulse excitation of [Ne]-like Ti and Ge has succeeded in saturated short pulse lasing at 32.6 nm and 19.6 nm with low pump energy level."

GJ Tallents, A Behjat, A Demir, JY Lin, R Smith, CLS Lewis, A McPhee, SB McCabe, PJ Warwick, D Neely, E Wolfrum, J Zhang, GJ Pert, PV Nickles, MP Kalachnikov, M Schnürer; "The optimization of soft x-ray lasers."

Conference on Laser and Electronics (CLEO), OSA Techn. Digest Series, Baltimore, USA (1997)

MP Kalachnikov, PV Nickles, M Schnürer, W Sandner, VN Shlyaptsev, C Danson, D Neely, E Wolfrum, J Zhang, A Behjat, A Demir, GJ Tallents, PJ Warwick, CLS Lewis; "Saturation in transient inversion x-ray lasers on [Ne]- like Ti and Ge"

Optimisation of Transient Gain
X-ray Laser for 20-32 nm

ABSTRACT

The development of X-ray lasers is marked by the progression toward shorter wavelengths using less drive energy. A recent X-ray laser experiment at the Rutherford Appleton Laboratory demonstrated saturated X-ray laser operation in the Ne-like Ti and Ge X-ray laser schemes at 32.6 and 19.6 nm respectively, with a drive energy of only a few joules, a significant step in the progression to table top systems. In this report we describe the laser development necessary to generate suitable travelling wave line-focus laser drive pulses and the transient population inversion X-ray laser results obtained.

BACKGROUND REVIEW

The brightest and most robust X-ray lasers to date rely on electron collisional excitation to pump electrons into the upper laser state, a quasi-steady state population inversion being formed due to the rapid radiative decay of the lower laser level with respect to the upper one. The most efficient schemes still require 100's of Joules of drive laser energy on target [i)] and in order to become practical and accessible for applications, X-ray lasers must become more compact and efficient. One problem with quasi-steady state schemes is that the regime in which Ne-like ions dominate is of too low an electron temperature to support optimum excitation rates.

A novel scheme, utilising a transient population inversion was proposed theoretically a number of years ago [ii,iii)]. It involves a combination of ns and ps duration optical pulses. The ns pulse is low intensity and preforms a column of plasma, heated sufficiently to produce an abundance of Ne-like ions. Once the Ne-like fraction is optimised, the high intensity ps pulse rapidly heats the plasma in a time-scale shorter than that of the relaxation processes of the excited states, and before any significant further ionisation can occur. Due to the ps pulse excitation, the transient inversion which occurs, is related to the different population rates of the levels via collisions and not determined by the slower relaxation rates of the excited levels relevant in the quasi-steady state quasi-steady state regime. This transient inversion is characterised by a short life time and theoretically yields much higher small signal gain values (10-100 cm^{-1}) as obtained in the quasi-steady state regime (several cm^{-1}) with long pulse pumping.

Recently a collisionally excited transient gain X-ray laser in Ne-like Ti with a gain value of 19 cm^{-1} on the 3p-3s 32.6 nm line at a low pump level of only a few Joules was demonstrated by the MBI group[iv]. By comparison, the most efficient quasi-steady state (long pulse driven) gain coefficient yet measured for Ti is 3.3 cm^{-1} [v,vi], requiring substantially higher drive energy. Simulations of the Ge X-ray laser transient population inversion scheme have also shown the possibility of ultra-high gains on a number of transitions [vii]. A peak local gain coefficient of 140 cm^{-1} has been predicted for the J = 0-1, 196 Å transition, which when ray traced to take account of refractive effects gives a ray averaged gain of ~30 cm^{-1}.

However, due to the restricted experimental conditions at the MBI, neither gain saturation nor significant shifting to shorter wavelengths could be demonstrated. Therefore, a joint experiment was carried out based on the high energy resources of the Vulcan CPA laser and the well proven RAL diagnostics to investigate some key parameters of this new transient excitation scheme for Ne-like ions. The aims were:

- Achieve saturation and characterise a Ti X-ray laser under the higher irradiance conditions available using Vulcan, utilising a travelling wave pump (see later) to sample longer target lengths.
- Demonstrating the practicality of scaling the scheme to higher Z materials, in order to reduce the XRL wavelength.

INTRODUCTION

The X-ray laser experiment was carried out on the VULCAN high power laser system, delivering synchronised nanosecond and subpicosecond pulses in a multi-beam configuration. Short pulse (ps) generation at ultra-high intensities is achieved using the technique of chirped pulse amplification (CPA). For this experiment both pulses were configured in line focus geometry and overlapped on target. The travelling wave was optimised by inserting a gold coated diffraction grating, and associated mirrors, at the output of the rod amplifier stage of the VULCAN laser chain. The first order diffraction imposes a tilt on the laser wave front in one dimension due to the path length difference across the beam. The near-field is imaged through the system and the tilt is preserved through the focusing system and onto target generating a travelling line focus. The short pulse was synchronised to the falling edge of the nanosecond long pulse allowing optimised plasma conditions to be formed.

In this report, the amplification characteristics of the 3p-3s (J=0-1) transition at λ= 32.6 nm and the 3d-3p (J=1-1) transition at λ= 30 nm were studied with plasma column lengths up to 10 mm. Also, the dependence of the X-ray lasing signal on the optical laser pump energy was measured, the X-ray beam divergence was determined and the total output energy of the X-ray laser pulse was estimated. For the first time saturation of the low pump energy X-ray laser utilising transient gain on the 3p-3s transition in Ne-like Ti at 32.6 nm and Ge at 19.6 nm was demonstrated.

EXPERIMENTAL SET-UP

The experimental set-up for this experiment involved reconfiguring the laser to provide a travelling wave, constructing a suitable line focus illumination system and diagnosing the X-ray laser and plasma conditions. These will be described in the following two sections

1. The Line Focus and Travelling wave
2. X-ray laser interaction and diagnostics

1. THE LINE FOCUS AND TRAVELLING WAVE

The creation of both the short and long pulse line focii relies on the optical aberration that is introduced by spherical mirrors operated at an angle relative to the optic axis. A schematic of the target chamber optical configuration is shown in figure 1. For the ultra-short CPA pulse the incoming laser beam is focused to a point (surrogate focus) using an off-axis parabolic (OAP) mirror. The spherical mirror then images this point source to the target plane. The angled nature of the spherical mirror introduces a large astigmatism into the beam producing two, one dimensional 'images' which are line focii. The second of the line focii which lies in the horizontal plane is the one that is used. The line focus always points toward the surrogate focus as can be seen from the geometry shown in Figure 1. The long pulse pre-ionising beam is delivered to target in a very similar way to the short pulse. The beam is brought to a surrogate focus using a 275 mm focal length lens and the line focus generated using a 315 mm focal length spherical mirror used off-axis.

The geometry leads to an inherent optical path difference between rays arriving on one side of the line focus with respect to the other. This optical path difference can be significant for the ultra-short pulses used. This means that the incident laser pulse will propagate from one side of the target to the other with a finite velocity that is normally several times the speed of light. This propagation velocity increases rapidly with reduced incidence angle onto the spherical mirror.

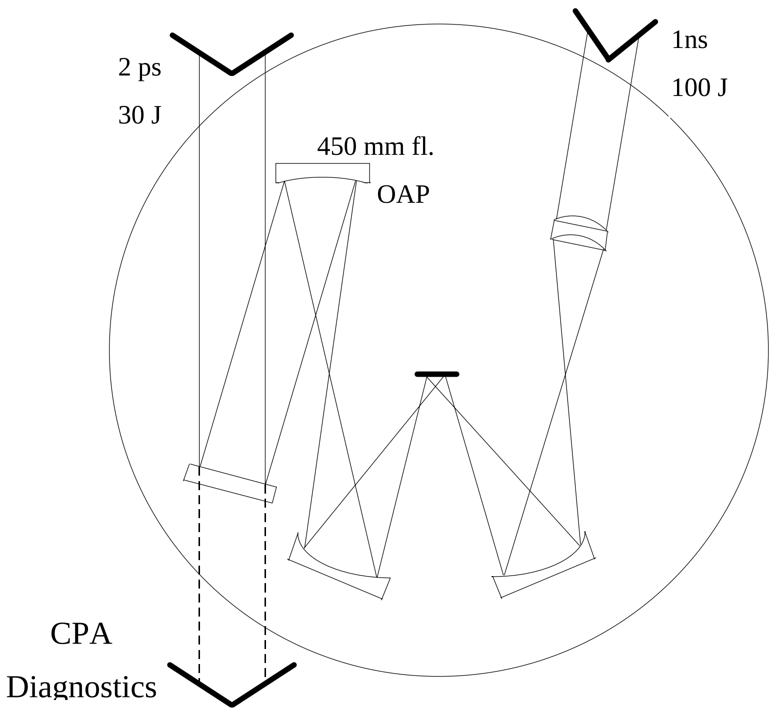

FIGURE 1. Optical layout of the target interaction chamber for the X-ray laser experiment.

The target lengths are typically 10 mm which means that the transit time for an X-ray laser photon from one end of the line focus to the other is typically tens of picoseconds. The X-ray laser upper state lifetime (gain) only lasts for a few picoseconds so if the plasma were to be formed at the same time everywhere along the line length then the gain at the end of the line will have dissipated by the time the X-ray photons arrive. The travelling wave effect can therefore significantly assist the X-ray laser process. One consequence is that the X-ray laser becomes directional with significantly higher output in the plasma propagation direction. The typical phase velocities encountered in this scheme are of the order 2-3 times the speed of light (c). Ideally, the phase velocity should be reduced to exactly c to ensure that that the X-ray photons always see the peak of the available gain throughout the whole length of the line.

The input beam dimensions to the target interaction chamber were 88 mm horizontally and 130 mm vertically. The off-axis parabola had a focal length of 450 mm producing a F5.1 surrogate cone. The spherical mirror, located 350 mm from the surrogate had a 350 mm focal length and was operated at an incidence angle of 15.5°. This gives a distance of 195 mm from the surrogate to line focus centre. This focusing system was modelled by the optical design program ZEEMAX[viii] which gave a propagation time of 15.9 ps over a 12.0 mm length line focus which gives a phase velocity of 2.5 c.

TABLE 1. Effect on the phase velocity of changing the angle of incidence onto the diffraction grating

Incidence Angle	Line focus length (mm)	Phase velocity
14.5°	10.24	0.95 c
15.5°	12.00	1.02 c
16.5°	13.87	1.08 c

1.ii OPTIMISATION OF THE TRAVELLING-WAVE

The phase velocity can be optimised by inserting a diffraction grating into the near-field of the incoming laser beam[ix)]. The dispersive nature of a diffraction grating means that an incident beam will experience a lateral time shear. The insertion of a diffraction grating into the beam will add to the inherent optical path difference that the beam experiences at the line. A schematic of the grating configuration is shown in figure 2. The correct choice of diffraction grating will then ensure that the plasma formation rate is equal to the speed of light.

The grating is inserted into the laser chain, at a point between the end of the rod amplifier system and the start of the disk amplifier system. This point was chosen because the beam flux is at a level which is below the threshold for laser damage of the grating and the beam aperture is <50 mm diameter allowing inexpensive commercial gratings to be used. The VULCAN laser

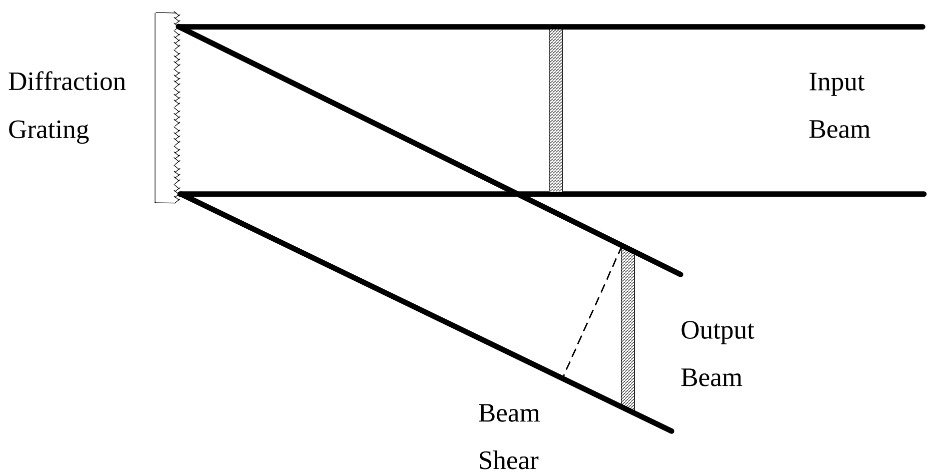

FIGURE 2. Schematic layout of the grating inserted to optimise the travelling line focus.

system is image relayed using a series of spatial filters between amplifier stages. The gating plane is therefore approximately imaged into the target interaction area. This imaging, coupled with the overall system magnification means that the pulse lengthening due to the dispersion induced by the grating is minimised.

For matching to 'c' a propagation time of 40 ps is required which equates to an extra 7.2 mm optical path length difference across the 88 mm input beam. However, account must be taken of the beam expansion encountered from the grating insertion point to the target area. The beam size is expanded by a factor of *3.8* so at the grating insertion point the additional path length required is 7.2 mm across a 23.3 mm beam. The diffraction grating line density required is 294 lines mm^{-1} when operated at normal incidence, the diffracted angle would be 18.4°. A commercial 300 lines mm^{-1} is used at the expense of introducing a 2 % increase in the path difference. This is however over compensated by the 5% change in beam size as a result of the diffraction. These factors result in a path difference of 7.0 mm using the commercial grating which gives a nominal overall path difference of 11.77 mm and a phase velocity of 1.02 c. It is possible to fine tune the phase velocity by changing the incidence angle onto the spherical mirror. Table 1 illustrates the possible tuning range.

The insertion of the grating, despite having its dispersion approximately cancelled at the target plane, will however impose a minimum pulse duration due to the spatial spectral shear that results from passage through the grating pulse compressor system. The shear imposed by the travelling wave grating is spatially dispersed by the compressor system. The shear angle is approximately 4.5° which for a sub picosecond pulse of 1.5 nm optical bandwidth (VULCAN output) gives a spatial dispersion of approximately 9 mm. This resulting time difference in the propagation direction is some 2.5 ps which when taken in quadrature with an incident pulse duration of 1 ps yields a theoretical minimum pulse duration of 2.7 ps.

The verification of the travelling wave was conducted using an streak camera with a sub picosecond resolution. Two metal spikes were positioned in the line focus and separated by 6.75 mm. The incidence angle was set to 14.5° giving a line focus length of 10.2 mm. The scattered light from these spikes was imaged onto the streak camera. The recorded separation in time of the spikes is about 14 ps. A further 8 ps must be added to correct for the viewing angle, yielding a 22 ps difference for 6.75 mm separation, giving a phase velocity of 1.02 c, exactly as expected.

2. EXPERIMENTAL DETAILS

The experiment utilised two 1ω 1053 nm beams incident on a single target in the Target Area West interaction chamber. A CPA beam provided up to 22 Joules on target in a ~7 ps duration pulse, coinciding temporally with the half maximum point on the falling edge of the long pulse. Different irradiance conditions were used for Ti and Ge targets. For Ti shots the long pulse was a roughly trapezoidal, 1 ns FWHM duration pulse, delivering an average of 20 Joules on target for an average intensity of 1.7×10^{12} W cm^{-2}. The short pulse delivered an average of 16 Joules on target for an average intensity of 2.2×10^{14} W cm^{-2}. For Ge the long pulse was a 600 ps FWHM Gaussian pulse delivering an average of 40 Joules for an average intensity of 5.6×10^{12} W cm^{-2}. The short pulse delivered an average of 21 Joules for an average intensity of 3.0×10^{14} W cm^{-2}. Titanium and Germanium stripes on glass, with a thickness between 0.6 and 1.0 μm and a width of about 200-300 μm as well as massive slab targets were used. The amplification length was varied by changing the target length. The targets were centred in the line focus to achieve maximum illumination uniformity.

The primary axial diagnostic (see figure 2) was a flat field, grazing incidence spectrometer with a 1200 lines per mm, aperiodically ruled grating, incorporating a cylindrical mirror for spatial resolution perpendicular to the dispersion direction. An XUV sensitive, back-thinned CCD was used to record time integrated spectra. Other diagnostics included a crossed slit camera and a space resolving crystal spectrometer to monitor uniformity of illumination and ionisation balance.

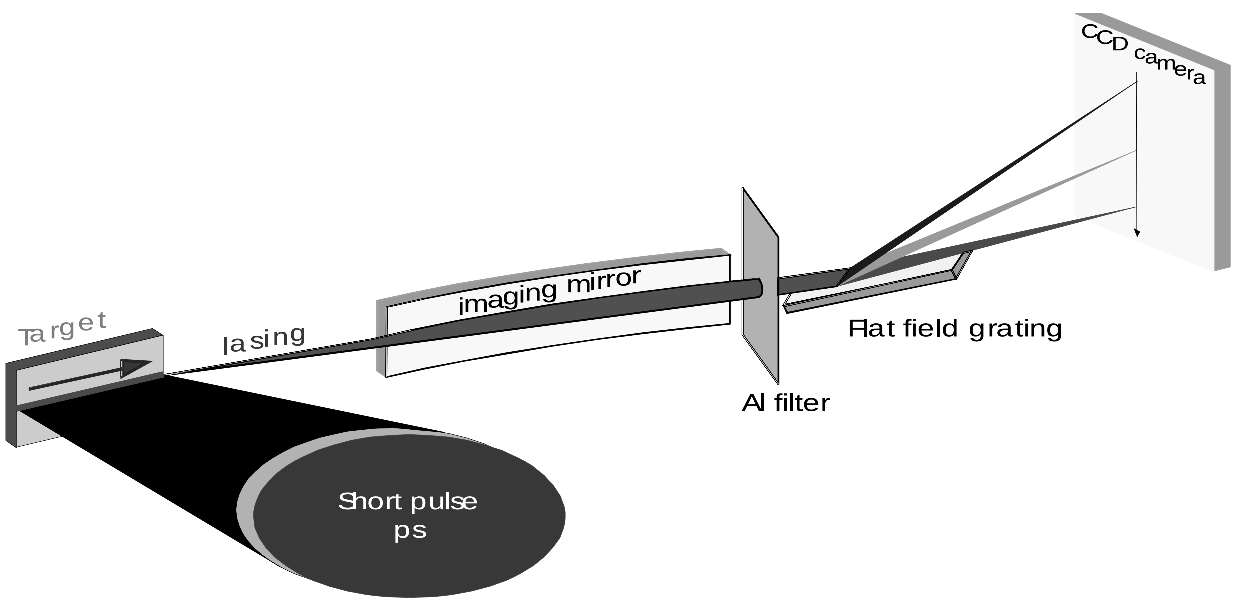

Figure 2 Schematic diagram showing the experimental set-up for the transient X-ray laser investigation.

RESULTS

The XUV lasing signals at 326 and 301 Å are shown as a function of the length of the Ti plasma column in figure 3. The 326 Å line is the 3p $^1S_0$ - 3s $^1P_1$ line, analogous to the 196 Å line in Ne-like Ge. The 301 Å line was first observed at MBI using the transient pump scheme [x)] but no gain measurement was possible and only a crude wavelength identification made. It has been suggested that it is a self-photo-pumped 3d $^1P_1$ - 3p $^1P_1$ transition [xi)].

The 326 Å lasing signals can be fitted [xii)] with a gain coefficient $g = 35\ cm^{-1}$ up to target lengths L ~ 3 mm. With further increase of target length the rate of increase of the output signal drops indicating a falling effective gain coefficient, an effect typical of a laser entering the saturation regime. Calculations for the 3p-3s Ti line have indicated [xiii)] that saturation should take place at a $\int g(l)dl$ ~15. As seen later, this occurs at L ~ 5 mm supporting the assertion of saturated output.

Further evidence of saturation is the behaviour of the 3d-3p line at about 301 Å. For the first time a gain coefficient $g = 15 cm^{-1}$ has been determined for this line. However, the 3d-3p line shows no saturation-like behaviour within the data fluctuations up to a target length of 10 mm. If it were refraction causing the drop in the effective gain coefficient of the 3p-3s line with increasing target

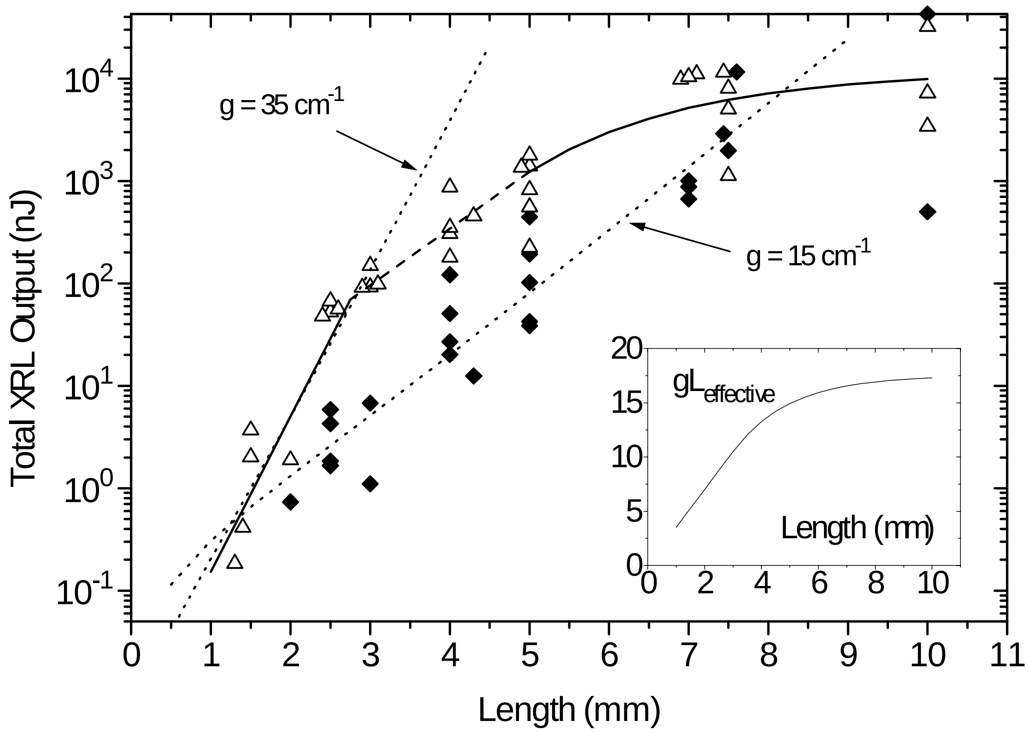

Figure 3 Output signals at 326 Å (Δ) and 301 Å (◆) as a function of target length for pump energies of 1.7 J/mm and 1.6 J/mm for the long and short pulses respectively. The inset shows how the effective gain-length product increases with target length, reaching "gL" ~ 15 at 5 mm.

length, then it would be expected that the 3d-3p line would also suffer a similar effect as simulations show both lines having their peak gain in similar plasma regions. The influence of any refraction on the X-ray beam should be nearly the same as a result of the small difference in the wavelength between the two lines. Temporally resolved measurements have also shown a simultaneous appearance and a comparable duration of these transient lasing emissions, revealing similar plasma conditions for them. This is the first observation of fully saturated operation of the 326 Å line in Ne-like Ti. Small gain-length products ($gL < 9$) were observed on other long pulse quasi-steady state Ti lasers at 326 Å but the 3d-3p line was not observed [v,xiv,xv)].

It is worth noting that the saturation of gain observed in the experimental data for the 326 Å line can be described approximately by a simple relationship of the form

$$g(L) = \frac{g_0}{1 + \frac{i(L)}{i_s}} \qquad (1)$$

where g_o = 35 cm^{-1} is the small signal gain coefficient determined from signal growth for lengths up to ~ 3 mm, $i(L)$ is the signal strength after amplification through a length of plasma L, i_s is the saturation intensity level of the signal, causing the small signal gain coefficient to be halved in magnitude and $g(L)$ is the effective local gain coefficient as the XRL pulse propagates along the plasma column. Self consistency is obtained with i_s ~ 500 (arbitrary units but corresponding to the numerical labels used in Figure 3) at L ~ 4 mm. The decreasing gain coefficient can be roughly estimated as $g(L) \sim 35 \exp[-(L-3)/2]$ for $L \geq 5$ mm from local fits to the data. Using these two expressions for $g(L)$ and extrapolating in the region $3 \leq L \leq 5$ mm we can construct a fit for $i(L)$ as shown in Figure 3. The general agreement is good. Assuming that $g(L) = 35$ cm^{-1} for targets $L \leq 3$ mm and $g(L) = 35 \exp[-(L-3)/2]$ for $L > 3$ mm, we can make an estimate of the effective gain-length product (i.e. $\int g(l)dl$) as a function of target length. This is shown as an inset to Figure 3 and it may be seen that an effective gL of 15 occurs for a target length of 5 mm. This is consistent with the saturation gL predicted from calculations as mentioned earlier.

Within the data fluctuation no systematic difference could be found in the output Ti lasing signals with or without the travelling wave grating in place. This suggests the inversion period was a significant fraction of the 33 ps transit time of a 10 mm target. For clarity only data recorded without the travelling wave (i.e. with the grating removed) are included in figure 3.

In another series of experiments we determined the threshold pump values for lasing at 326 Å as depicted in Figure 4, which shows outputs from 3 mm targets.

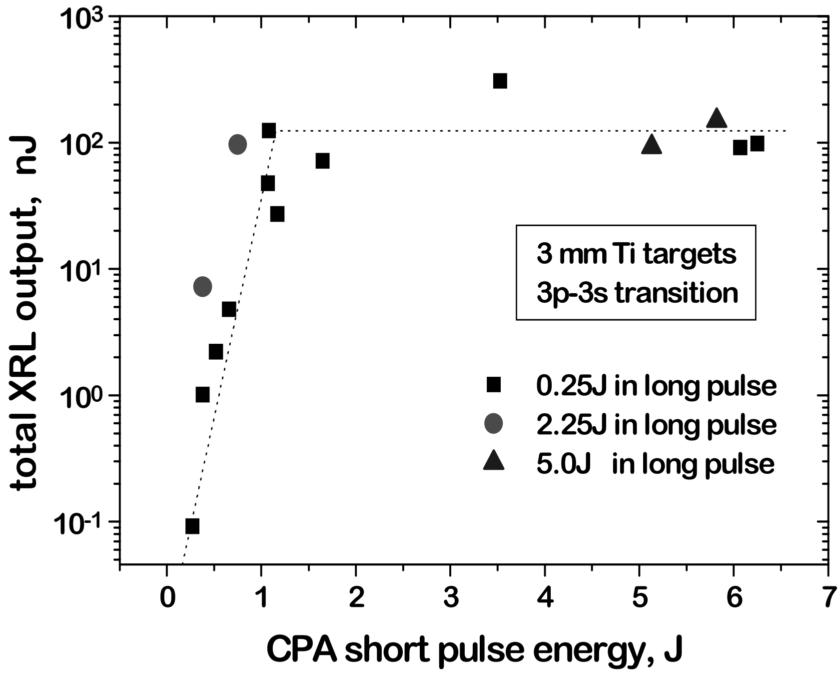

Figure 4 Peak output signals at 32.6 nm of 3 mm targets versus pump energy in the short pulse at fixed pump energies in the long pulse.

With E_{short} = 1.5 J for the short pulse and E_{long} = 0.25 J for the long pulse we observe the same output signal strength as recorded for Figure 3 conditions. This indicates that the gain coefficient is comparable and that we achieved a gain-length product of 10.5 for these reduced input energies. Pump energies as low as E_{long} = 0.25 J and E_{short} = 0.25 J yield measurable amplified emission. This verifies that X-ray lasing in the Ne-like Ti system is possible with table top class pump lasers. With E_{short} = 1.5 J one achieves the maximum XRL signal output in this pumping geometry. An increase in the long pulse intensity up to a factor of more than 10 did not give a higher output signal providing E_{short} was greater than 1.5 J. However, within the threshold region (E_{short} < 1.5 J) the lasing output was sensitive to E_{long}. Using the short or long pulse alone, no lasing was visible with the maximum energies used in this experiment.

From our experimental results we also tried to get more confidence in the wavelength determination of the 3d-3p (J= 1-1) lasing transition in Ti at 30 nm. Theoretical calculations [iv,xvi] cover the wavelength range between 29.1 and 30.0 nm. From the first transient inversion Ti experiments with the MBI CPA-Glass laser we estimated (restricted by the limited spectral resolution of the equipment) a wavelength at about 30 nm. Now, taking 32.65 nm for the 3p-3s line, 19.6 nm for the 3p-3s lasing line in Ge and 17.065 nm for the Al-L absorption edge (visible in first and second order in the spectra) which we recorded without changing the set-up, we estimate with a quadratic fit concerning the dispersion characteristic in that region a wavelength for the 3d-3p line of (30.15±0.05) nm.

The transient scheme was also successful in pumping the Ne-like Ge X-ray laser on the 3p $^1S_0$ - 3s $^1P_1$ (J = 0-1) transition at 196 Å. The rapid increase of X-ray laser signal with target length is illustrated in Figure 5. For lengths up to 5mm this growth is exponential and can be fitted using a small signal gain coefficient of 30 cm^{-1}. Signals from lengths greater than 5 mm deviate from this trend of exponential growth, the rate of increase of output slowing. As mentioned previously this is a characteristic feature of a laser going into saturation, the inversion being significantly reduced by the number of stimulated transitions. However in this case the curling over effect is not due to saturation. When the energy in both beams was halved for one shot we saw no lasing signal. For all shots illustrated the target was positioned in the centre of the line focus. However, when a 5 mm target was positioned to one side of the 10 mm line focus lasing signal was reduced by an order of magnitude. These shots indicate that the lasing signal is strongly dependent on the incident intensity, an effect already observed around the threshold incident intensity for Ti. We believe that for targets longer than 5 mm the intensity towards the ends of the target was low enough compared to the centre to decrease the local gain coefficient and prevent continued exponential growth with target length. However, 5 mm targets exhibit a gain-length product of 15 which is approaching that

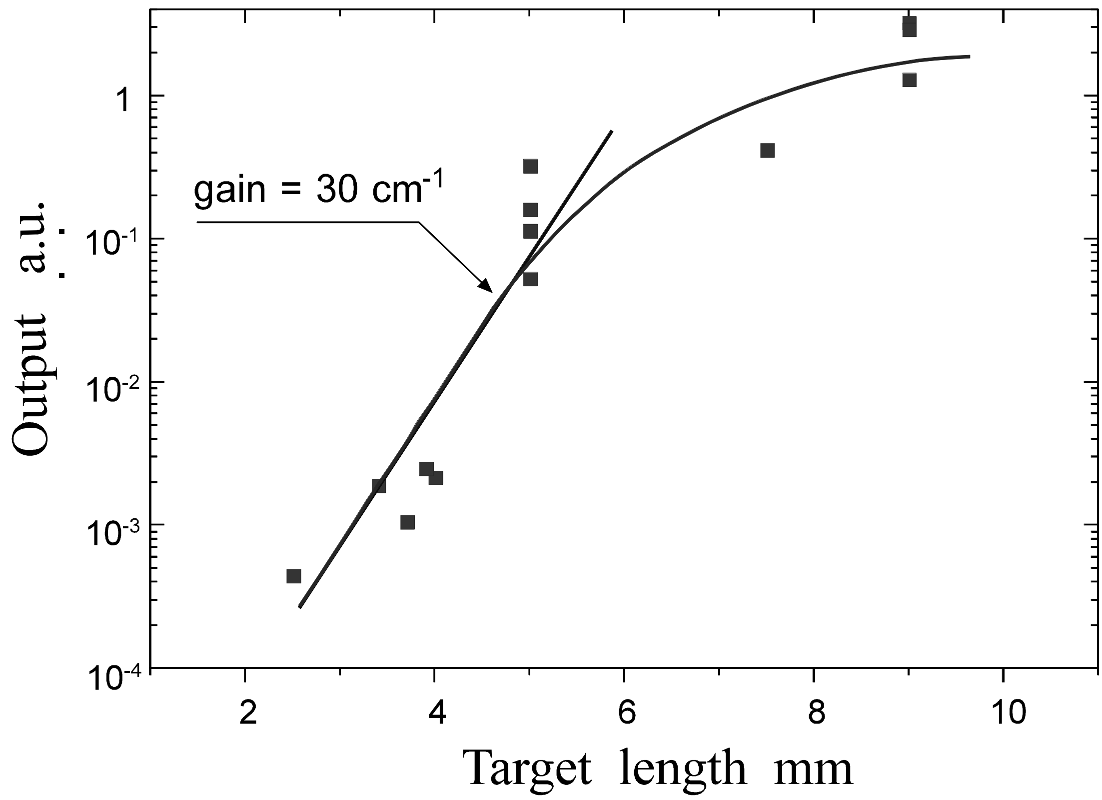

Figure 5 Saturated Ge XRL at 19.6 nm. Peak output signals versus target lengths.

required for saturation. Also, taking the average energy output from 9 mm targets (13 μJ) and assuming a 20 ps pulse duration from a gain zone area measuring 100 μm by 100 μm, gives a conservative output intensity estimate of 6.5×10^9 W cm^{-2}. This is close to the calculated [i] saturation intensity of 2.0×10^{10} W cm^{-2}, although the different plasma conditions imply a different recovery time, t_{rec}, and hence the two values are not directly comparable.

Shots where the TW grating was removed showed between one and two orders of magnitude less lasing output from 9 mm targets. Null shots, where only one of the two beams was fired, confirmed that lasing only occurred when the target was irradiated by both pulses. No Ne-like resonance line emission was visible on the crystal spectrometer from the long pulse alone. Figure 5 shows the spectrum obtained when both beams irradiated the target (bold line). For comparison a spectrum obtained with the same instrument from a typical quasi-steady state pumping scheme is shown also (fine line). The quasi-steady state scheme used was [i] two 75 ps FWHM duration pulses, separated by 2.2 ns, the first pulse having 20% the intensity of the second, which had an intensity on target of 4×10^{13} W cm^{-2}. However, very similar spectra are obtained using ns pulses. The Ne-like 3d-2p lines in the quasi-steady state spectrum (the two brightest lines) had a time integrated intensity of 5

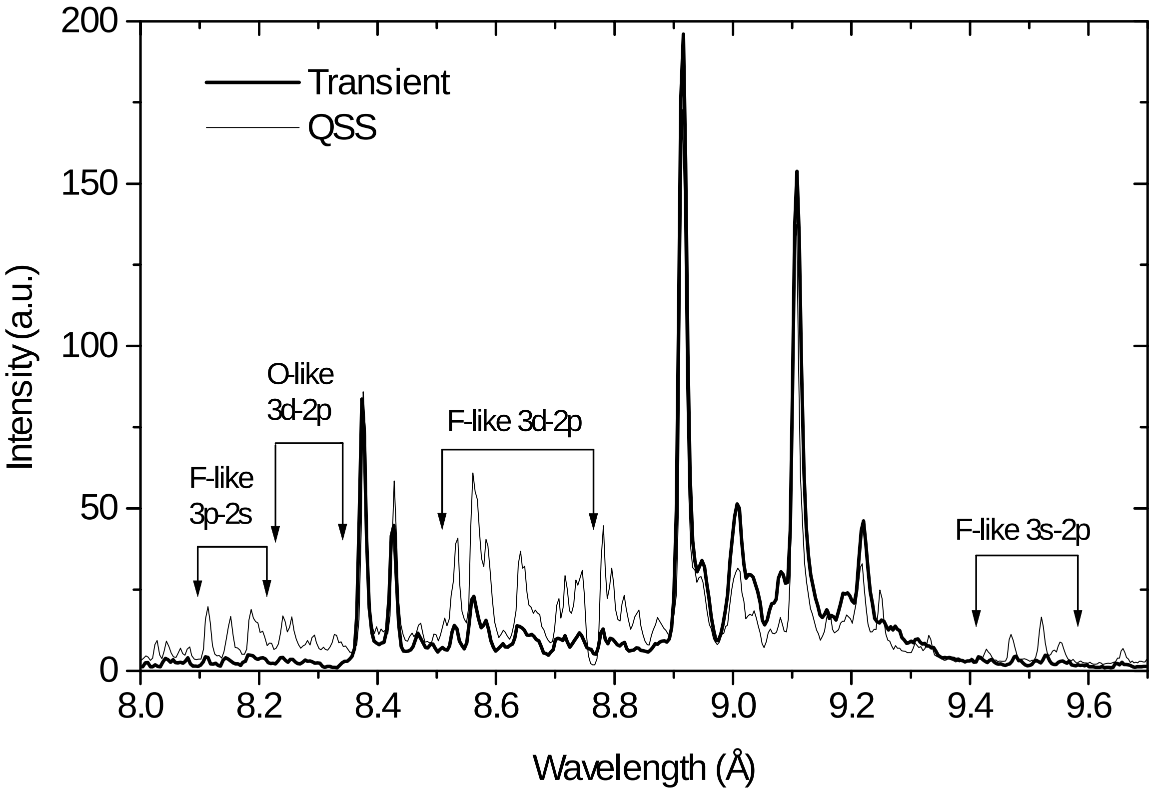

Figure 6 Resonance line spectra obtained using a KAP crystal spectrometer. The bold line is the spectrum obtained using the transient pump scheme. The fine line was obtained by the same instrument from a Ge target pumped with the quasi-steady state scheme.

times that obtained using the transient scheme. The quasi-steady state spectrum has thus been scaled down to make the intensity on the Ne-like 3d-2p lines the same. Comparing the two spectra we see that F-like and O-like lines have been suppressed by using the transient scheme rather than the quasi-steady state scheme. Compared to the Ne-like emission, the brightest F-like 3d-2p line at 8.56 Å is relatively three times weaker under the transient scheme. We have thus created a large population inversion without wasting so much energy over-ionising the plasma.

CONCLUSION

Summarising we can state, that as a result of the excellent optical parameters and the operational reliability of the pump laser, the complex diagnostic and the technical support, accessible at the RAL during the campaign the results have surpassed our aims. Saturation of the 326 Å line in Ne-like Ti has been achieved for the first time due to a gain coefficient of 35 cm^{-1}. Measurable amplified emission was observed from 3 mm targets for a total pump energy of 0.5 J, representing a truly table-top system. A second 3d-3p laser line has been identified at 301.5 ± 0.5 Å and a gain coefficient of 15 cm^{-1} measured. This is 1- 2 orders of magnitude in pump energy reduction as compared to common quasistationary XRL systems. Additionally, the XRL divergence was determined to be about 5-10 mrad.

The output energy in the range of several tens of uJ corresponds to a very high Ti XRL efficiency of $\sim 10^{-5}$. With its predicted ultra-short pulse length this laser has applications for high temporal resolution probing of other laser produced plasmas. Finally, it is worth mentioning that the new efficient XRL excitation is not only restricted to neon like schemes but should be also attractive for nickel like as well as innershell transitions opening a route to short wavelength low sized X-ray laser. Therefore, related experiments will be a matter of future experiments.

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