**The Effect of Prepulse on X-Ray Laser Development
Using a Powerful Subpicosecond KrF* Laser**

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ABSTRACT

A high power u.v. laser has been developed as a pump source for short wavelength (down to 1 nm) x-ray lasers. Various schemes are considered and theoretical analysis is discussed. Spectroscopic studies of laser-target interaction have been performed and, in particular, the effect of a prepulse on plasma generation has been investigated. Analysis of the observed spectra indicates that reduction of the prepulse energy results in a higher temperature plasma. Investigation of the interaction using thin layered targets is also presented. These data provide evidence for initially hot plasma conditions generated from target layers ≤ 150 Å. Discussions of proposed laser schemes at 1 - 5 nm are presented.

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1. Introduction

X-ray laser research is being pursued in many laboratories around the world (see e.g. references 1-8). At Princeton University, a recombination scheme⁹ (using a magnetically confined plasma as the gain medium) has produced x-ray laser emission at a wavelength of 18.2 nm. The output beam has been shown¹⁰ to have a divergence of ~5 mrad, pulse energy of ~3 mJ and a duration of ~10 ns. This soft x-ray laser is presently being applied to contact microscopy of biological specimens¹¹ and may soon be used in imaging microscopy and microlithography.

In addition to this research, much effort is being directed at increasing the output energy of the soft x-ray laser. This involves both the development of a laser cavity by using multilayer mirrors^{12,13} and, also, the use of amplifying stages produced by a second pump laser.¹⁴ In this latter case, an amplifier designed to be used with the soft x-ray laser at 18.2 nm, was developed using a 25J Nd:glass pump laser and had a measured gain of 8 cm^{-1} . A similar, though a smaller aperture, amplifier was developed using as little as 6J of pump energy.^{13,14}

A research direction which attracts much interest and which is the primary subject of this paper involves the extension of x-ray laser schemes to shorter wavelength emission (down to 1 nm). In x-ray laser applications, a development of this type would provide greater resolution, better penetration and, in microscopy, potentially higher contrast.

To generate shorter wavelength x-ray lasing, the scaling of the "pump" laser power, energy and duration are such that a high power density ($>10^{18}$ W/cm²), short pulse (<1 ps) laser system would seem to be the appropriate choice for the pump source. This motivated our construction of the powerful, subpicosecond laser (PSP-laser) system.¹⁵ In addition, however, shorter output wavelength generally involves transitions which arise from excited levels of highly ionized species. The laser characteristics required to produce the relatively long-lived ionization stage are very different from those needed to excite the short wavelength transition and to produce a population inversion. While a single laser might be able to perform these tasks, a two-laser approach,¹⁶ which separates these processes, promises to be more efficient.

The two-laser approach, which is being developed at the Princeton University Plasma Physics Laboratory (PPPL), is shown schematically in Fig. 1 and can be described as follows. A high energy CO₂ or Nd:glass laser is fired onto a target to produce a plasma column. A 100-150 kG magnetic field is used for confinement, providing control of the target plasma conditions. The PSP-laser is then fired at the appropriate time (the occurrence of the correct stage of ionization) to create the population inversion.

Several schemes to generate short wavelength x-ray lasing have been examined. It has been proposed¹⁷ that very high power density, short pulse length lasers could be applied to multiphoton excitation of inner shell transitions in order to generate x-ray lasing. Use of metastable levels for storage of the pumping energy¹⁸ represents a promising technique which may also lead to shorter wavelength emission. Still other approaches¹⁹⁻²² are

based on inner shell ionization and Auger transitions. In these schemes it may be practical to use a laser-produced flash of high energy x-rays to pump the lasing transitions. A high power, subpicosecond KrF* laser would be an excellent driving laser in such an approach.

In some of these schemes, the presence of significant prepulse could result in a preformed, expanding plasma which may play a very negative role in the creation of plasma conditions appropriate for the production of x-rays. In this paper we examine, primarily, the role of a prepulse in laser-target interaction. We consider some techniques for the removal of prepulse energy and also discuss alternative approaches for which prepulse effects may be less important.

A brief description of the laser is presented in section 2 and an analysis of the role of a prepulse in this interaction is the subject of section 3. In section 4 an investigation of the interaction of the picosecond pulse with layered targets is presented. This study was performed to provide evidence of the scale lengths associated with the creation of hot plasma conditions. Section 5 introduces some theoretical studies related to the development of short wavelength x-ray lasers.

2. The PSP-Laser System

The generation of very short duration, high power ultraviolet laser pulses is a relatively new and complex development.²³⁻²⁶ The PSP-laser has developed in two stages. The first stage has been described in detail earlier.¹⁵ It provides

an output energy of approximately 25 mJ in a pulse duration of 1 ps. This stage has been used in laser-target interaction experiments which showed the occurrence of highly charged species as well as significant line broadening and distinct line asymmetries.²⁷ The experiments investigating the role of prepulse energy in plasma generation also used only the first stage of this laser system. The second stage of the PSP-laser incorporates pulse compression,²⁸ which provides a 200-300 fs pulse duration, and a final, 5 x 10 cm aperture, 80 cm long, KrF* amplifier (constructed at PPPL²⁹). The measured output energy of this final amplifier (in a double-pass configuration) is 150-200 mJ. This should result in power density at focus of $>10^{18}$ W/cm² and electric field strength >1 kV/Å (two orders of magnitude greater than the atomic binding field in Hydrogen). A detailed block diagram of the complete system is given in Fig. 2.

The first stage of the PSP-laser consists of a commercial dye oscillator (a dual dye jet system) pumped by the frequency-doubled output of a mode-locked cw Nd:YAG laser. DCM dye is used and the cavity is tuned to an output wavelength of 648 nm. Residual 1.06 μ m radiation from the YAG laser is directed through a pulse selector, amplified, frequency-doubled and used to pump a three-stage dye amplifier. The output of the dye amplifier is frequency doubled and then mixed with residual 1.06 μ m radiation (in BBO and KDP crystals, respectively) to yield a seed pulse for the KrF* excimer amplifiers with the desired 248 nm wavelength. Optionally, prior to injection into the dye amplifier, the pulse width can be compressed using a fiber-grating pair. For the experiments presented here, however, pulse compression was not implemented.

The pulse duration is typically measured at the output of the dye oscillator, the dye amplifier, and the second excimer amplifier. In the ultraviolet region, a scanning autocorrelator using two-photon fluorescence was used to determine the pulse width. The pulse duration has also been measured up to the output of the second KrF amplifier with the pulse compression system in place. The results, shown in Fig. 3, indicate a pulse width of 200-300 fs. A single-shot autocorrelator³⁰ using three-photon fluorescence is under development for measurement of the pulse width after the final KrF* amplifier.

3. Effect of Prepulse on Plasma Generation

The experimental layout for these measurements is shown in Fig. 4. The first stage of the PSP-laser system was used, providing ~25 mJ in ~1 ps focussed to a power intensity of $\sim 10^{16}$ W/cm² on various solid targets. The targets were cylindrical and rotated to a fresh surface prior to every laser interaction with the target. A 2-m Schwob-Frankel soft x-ray spectrometer, SOXMOS,³¹ was used to diagnose the interaction. This spectrometer was equipped with a multichannel detector and covered the wavelength region of 5 - 340 Å. Each output spectra represents the integration of approximately 200 exposures. At a repetition rate of ~2 Hz, a spectrum was obtained in 2 minutes.

The 248 nm laser pulse has two components. First, there is the short duration (~1 ps) pulse which is amplified through the KrF* amplifier chain and, second, there is a long duration (~10 ns) amplified spontaneous emission

(ASE) pulse which is coupled from the first KrF* amplifier to the second. An additional amount of ASE coming directly from the second amplifier is spatially separable from these other components. However, the two primary components behave very similarly in terms of focusing characteristics and, without the use of a saturable absorber, could only be separated temporally. The injection timing of the seed pulse is controlled very precisely using a digital/analog timing system (the Picosecond Delay Timer³²) referenced to the frequency of the mode-locking crystal of the pump laser for the dye oscillator. As shown in Fig. 5, the amount and duration of the ASE prepulse can be changed by varying the injection timing of the seed pulse. The output energy of the picosecond pulse is maximum around the peak of the ASE. This injection time is defined as $t = 0$. The picosecond pulse energy varies only slightly ($\sim 5\%$) when injected at times $t = \pm 3$ ns from this point. This is in part due to saturation effects in the second KrF* amplifier. The effect of the timing jitter of the KrF* amplifiers (± 1 ns) was averaged statistically by collecting the spectra over 200 shots. The long term drift of the amplifiers was carefully monitored and compensated, but was not a major problem over the time period of the experiment.

The spectra shown in Figs. 6 a-c were obtained using a teflon target and injecting the seed pulse at times, relative to the peak of the ASE signal, of $t = -3, 0$, and 3 ns, respectively. To minimize any system variations during the experiment these data were collected in a non-stop series of discharges. This was possible by utilizing a large memory unit of the CAMAC system; a series of data was, first, collected and stored in the memory unit and, later,

analyzed. The estimated amount of prepulse energy relative to the picosecond pulse energy was 0.3% ($t = -3$ ns), 7% ($t = 0$ ns), and 15% ($t = +3$ ns).

It is clear from the spectra in Fig. 6 a-c that as the injection time is delayed and there is more prepulse energy on target, the F VII lines become increasingly broad. Previous analysis of laser-target interaction with the PSP-laser system has shown²⁷ that the observation of broadened lines can be explained in terms of Stark broadening. The electron density estimated from line broadening, especially in the case of a weak prepulse ($t = -3$ ns), is smaller than the critical electron density for 248 nm radiation (in the interaction with a solid target, the critical density represents a lower limit for the maximum attainable electron density). In this experiment, the F VII line emission occurs in the lowest density plasma under the condition of weakest prepulse. Assuming that the plasma evolution is similar in all cases, this implies that the condition of weak prepulse produces the highest temperature plasma. Calculations verifying this observation are provided below. Additionally, much stronger resonance lines of C V and C VI (observed in third order) and much stronger F VIII $1s3d-1s2p$, 98.8 Å emission were observed when there is only a weak prepulse ($t = -3$ ns) as compared to the case of a stronger prepulse ($t = 0$ ns and $t = +3$ ns). This shows that a hotter plasma is created with less prepulse.

The role of the prepulse may be considered as follows. When there is a negligible amount of prepulse, the picosecond pulse would be expected to interact directly with the solid target, producing a virtually solid density plasma. If, however, there is enough prepulse energy, the picosecond pulse

will interact with a preformed, expanding, low temperature plasma. As the amount and duration of the prepulse increases, the size of the target plasma increases and the laser energy is distributed over a larger number of ions. The result, then, is a decrease in electron temperature with increased prepulse energy and, therefore, the appearance of F VII lines earlier in time when the electron density is still high. The following calculations and modelling provide estimates of the initial plasma conditions associated with varying prepulse energy.

The time-integrated spectra of Fig. 6 contain several transitions of the F VII ion. Plasma parameters corresponding to this radiation can be estimated as follows. The populations of $n = 3$ and $n = 4$ levels of F VII follow local thermodynamic equilibrium³³ (LTE) when $T_e = 50$ eV and $N_e = 10^{21}$ cm⁻³. In this case, the intensity, I_{ji} , of the radiative transition from level j to level i is proportional to the radiative decay rate times the Boltzmann factor,

$$I_{ji} \propto A_{ji} g_j \exp(-E_j / T_e) \quad (1)$$

where A_{ji} and g_j are the radiative decay rate and the level degeneracy, respectively. Using Eq. (1), the electron temperature can be obtained from the intensity ratio of F VII 4d-2p and F VII 3p-2s since the populations of levels 4d and 3p are temperature dependent. As mentioned, previous analysis of spectra resulting from the interaction of the PSP-laser with solid targets used a modified quasi-static ion Stark broadening theory³⁴ to give the line broadening of the F VII 3d-2p transition. In this study the broadening of the F VII 3p-2s

line was used to determine the electron density since this line is less susceptible to self-absorption than the F VII 3d-2p line.

In an optically thin plasma the theoretical ratio of the intensities of the F VII 3d-2p and 3p-2s lines is 5.4. Since the optical thickness³⁵ of the F VII 3p-2s transition is seven times smaller than that of F VII 3d-2p, a comparison of the observed ratio to the theoretical ratio gives the transmission factor of the F VII 3d-2p emission line (assuming negligible re-emission). From this factor and with a value for the population of the F VII 2p level, one can obtain an estimate of the plasma thickness. The population of this level can be estimated by determining the ion density and assuming both the charge distribution of the fluorine ions and the fraction of the ground state population of F VII ions. In this case, where the F VII lines dominate all other radiation, the fraction of F VII ions was assumed to be 0.5 and the fraction of the ground state population was taken to be 0.75 (could be improved with a more rigorous calculation of ionization balance). Once the plasma conditions associated with the emission from the F VII ion have been determined, the parameters at earlier times in the plasma evolution can be estimated by taking the major energy loss mechanisms into account and characterizing the expansion of the plasma.

The major energy loss mechanisms are radiative cooling, thermal conduction, and adiabatic cooling. Radiative cooling (estimated from the resonance lines of fluorine and carbon ions) is an order of magnitude less than adiabatic cooling and, so, is neglected. The time scale, τ_c , for thermal

conduction due to the interaction of a heated plasma slab with a surrounding cold plasma can be estimated from,³⁶

$$\tau_c = \{60 N_e Z e^4 (m_e)^{1/2} x_0^2 \ln \Lambda\} / \{(4\pi\epsilon_0)^2 (kT_e)^{5/2}\} \quad (2)$$

where Z is the average charge state in the cold plasma, x_0 is the heated plasma slab thickness, and $\ln \Lambda$ is the Coulomb logarithm. For electron density of $\sim 10^{22} \text{ cm}^{-3}$, electron temperature of 200 eV, and scale lengths of 0.2 μm this rate is on the order of 10 ps, significantly longer than the time scales considered here. For this reason thermal conduction has also been neglected in this analysis and, consequently, the time evolution of the plasma parameters was estimated using adiabatic cooling only. For higher density and temperature ($N_e = 10^{23} \text{ cm}^{-3}$, $T_e = 300 \text{ eV}$) and smaller scale lengths ($x_0 = .05 \mu\text{m}$), characteristic of the plasma at earlier times, this time scale decreases to $\sim 2 \text{ ps}$. This begins to approach the time scales considered in this model and indicates that thermal conduction may become important in modelling the behavior of the plasma at very early times.

The results of the calculations are summarized in Tables 1a, b. The parameters indicated in the last row of these tables are those extracted from the spectral data (Fig. 6) while those at higher electron density ($N_e \sim 10^{23} \text{ cm}^{-3}$ and $2 \times 10^{22} \text{ cm}^{-3}$) are estimated assuming that the plasma expands adiabatically. The reduction of electron density due to the change of ionization stage of C and F ions during recombination was estimated by assuming the ionization stages specified in Table 1. These stages were based on the observed spectra and the estimated electron temperature.

Table 1a gives the plasma parameters for the case of a weak prepulse ($t = -3$ ns). Estimates of the plasma parameters were made until the estimated plasma thickness was comparable to the expansion during 1 picosecond (the laser pulse duration). An expansion velocity³⁷ of 5×10^6 cm/s was used for the initial plasma density of $N_e = 10^{23}$ cm⁻³ and subsequent expansion velocities were obtained from energy conservation.³⁸ This analysis indicates that an initially hot plasma of $T_e = 300$ eV and $N_e = 10^{23}$ cm⁻³ quickly expands to $T_e = 130$ eV and $N_e = 2 \times 10^{22}$ cm⁻³ in 2 picoseconds and to $T_e = 45$ eV and $N_e = 4 \times 10^{21}$ cm⁻³ in 4 picoseconds.

Table 1b indicates that with a larger prepulse the initial electron temperature at $N_e = 2 \times 10^{22}$ cm⁻³ was colder than it was in the case of a weak prepulse. There are no temperature estimates at higher density (10^{23} cm⁻³) since the plasma scale length (1300 Å) at these densities greatly exceeds the expansion distance during 1 picosecond. This situation is unrealistic in terms of the picosecond pulse interaction.

For the case of largest prepulse ($t = +3$ ns), the density associated with the F VII emission was 8×10^{21} cm⁻³. This density value, greater than in the previous cases, suggests that the F VII emission occurred earlier in time relative to the interaction of the high power, picosecond pulse. If the emission occurred during the laser pulse then some of the line broadening and line asymmetries associated with this data may be due to direct interaction of the extremely high electric field associated with the laser pulse. Effects of Stark broadening due to high plasma density and effects due to the intense electric

field of the laser could be separated through the use of still higher intensity laser pulses or by providing lower plasma density conditions.

4. Interaction of Picosecond Laser Pulse with Layered Targets.

The analysis of section 3 indicates that a plasma of $N_e = 10^{23} \text{ cm}^{-3}$ and $T_e = 300 \text{ eV}$ is created in a layer of $\sim 500 \text{ \AA}$ thickness. The amount of target thickness necessary to create this plasma is only about $100 \text{ \AA}$. To determine if the picosecond laser pulse is interacting with such a thin layer of target material was tested with the use of layered targets.

Targets made up of a $150 \text{ \AA}$ thick Fe coating on an Al substrate were prepared for this purpose. The Al substrate was first micro-polished to minimize effects resulting from surface irregularities. The layer thickness was determined from mass deposition which was monitored during the coating process using a quartz crystal mass balance. The substrate was rotated during the coating process in order to obtain a uniform coating around the cylindrical surface.

To provide reference spectra for the analysis of the interaction with the layered target, spectra from solid Al and Fe targets were first obtained. These are shown in Figs. 7a, b. The spectrum obtained from the solid Fe target shows Na-like Fe XVI and Mg-like Fe XV. Since Fe XVI is the highest ionization stage observed using the first stage of the PSP-laser, this spectrum can be used to indicate the early stages of plasma development. The spectrum from the solid Al target, shown in Fig. 7a contains several lines from ionization stages from Al VI to Al X. Since the highest ionization stage observed is Al XI, these lines

from lower ionization stages were generated later in time. This spectrum can be used to indicate the existence of a hot Al plasma.

Figure 8 shows spectra obtained with a layered target consisting of 150Å layer of Fe on a substrate of Al. The number of shots integrated to obtain this spectra was reduced to half of those used in the interaction with the solid Al and Fe targets shown in Fig. 7. This was done simply to obtain more spectra under different experimental conditions. The intensity of these spectra, therefore, should be multiplied by a factor of two in making quantitative comparisons with the spectra from the uncoated targets. The injection time of the seed pulse was $t = -1.5$ ns in Fig. 8a and $t = -3.0$ ns in Fig. 8b. The differences in the observed spectra between these cases show how important a role the amount of prepulse plays in the interaction of the picosecond KrF* laser with a layered target.

Figure 8a shows strong lines from the Al plasma and very weak lines of Fe XVI and Fe XV. This implies that the level of prepulse contained in the case of $T = -1.5$ ns (3% of energy) is enough to evaporate most of the 150Å Fe coating and the interaction of the picosecond KrF* laser with the ablated Fe does not create a hot Fe plasma.

Figure 8b obtained using a minimal amount of prepulse (~0.3%) contains radiation mostly from the Fe plasma and shows the interesting feature that the intensities of Fe lines obtained with a target of 150Å thick Fe layer are virtually the same as those obtained with the solid Fe target shown in Fig. 7. This implies that the observed radiation from the Fe XVI and Fe XV ions are

generated from target material thicknesses $\leq 150\text{\AA}$. Furthermore, the additional observation of weak Al lines implies that the initial thickness of the interaction region between the picosecond KrF* laser pulse and the Fe target is less than $150\text{\AA}$, and heat conduction from the hot plasma toward the cold solid target region does not contribute significantly to the creation of hot plasma.

5. Theoretical Analysis Of Alternative Paths To 1-5 nm Lasers

The theory initiatives at PPPL, related to achieving lasing action below 5 nm and down to 1 nm, fall into two general categories. In the first, assessments are being made of the feasibility of scaling successful recombination laser experiments from 18.2 nm in carbon to higher Z elements and shorter wavelength transitions. One possibility under consideration is the H_α line in hydrogen-like aluminum at 3.9 nm. Possible designs and sensitivity to laser parameters are discussed below. The second line of investigation centers on using the electric field of the PSP-laser directly as a pump rather than ultimately as a source of heat. In this regard, it may be possible to either selectively excite a transition in or to produce additional ionization from an ionic state which is created by other, much lower power, energy sources such as a long-pulse, high energy CO₂ or Nd:glass laser. This forms the previously mentioned "two-laser approach" to x-ray lasing.

We will first present calculations which suggest that it should be possible to scale successful recombination laser experiments in H-like Carbon at 18.2 nm to 3.8 nm by scaling to H-like aluminum and shortening the laser pumping and recombination time scale from the nanosecond to the

picosecond range. We demonstrate that free expansion of laser-irradiated foils of thickness $\sim 100\text{\AA}$ can provide the necessary cooling rate and the appropriate density and temperatures required for significant gain, approaching 10^3 cm^{-3} .

The utility of the design presented here is that, although the pulse shape required of the pumping laser in order to achieve gain must be well-defined (i.e., minimal prepulse), the energy requirements are modest ($\sim 10\text{ J/cm}^2$).

The optimal conditions for recombination pumped gain are that the plasma density be as high as possible without collisionally quenching the lasing transition, $n_e \leq n_{e,q}$ where

$$n_{e,q} \equiv \frac{A_{ul}}{C_{ul}}, \quad (3)$$

with C_{ul} and A_{ul} , respectively, the collisional de-excitation rate and spontaneous decay rate between the upper and lower levels and n_e is the electron density. Isoelectronic scaling with nuclear charge Z for H-like ions yields $C_{ul} \propto Z^{-3}$, $A_{ul} \propto Z^4$, so that $n_e \propto Z^7$. The requirements on the electron temperature T_e are that it change from a value comparable to the ionization potential E_{ion} to a small fraction thereof in a time short compared to the recombination time $\tau_{\text{rec}} \equiv (n_e \alpha_{\text{rec}})^{-1}$.

In the case of H-like aluminum $C_{32} = 1.5 \cdot 10^{-10}\text{ cm}^3\text{ sec}^{-1}$ and $A_{32} = 1.2 \cdot 10^{12}\text{ sec}^{-1}$, yielding $n_{e,q} = 8 \cdot 10^{21}\text{ cm}^{-3}$. The ionization potential I_p of the

last electron is $2.3 \cdot 10^3$ eV. For $n_e = n_{e,q}$ and $T_e = 0.1 \cdot I_p = 230$ eV, the three-body recombination rate³⁹ is $\tau_{rec} = 2.5 \cdot 10^{-12}$ sec which indicates a necessary cooling time of a few psec if substantial gain is to be achieved.

Having estimated the plasma parameters and the recombination rate, the expected gain can now be estimated as well. The formula for the line-center gain coefficient

$$\kappa = \frac{\lambda_{ul}^4 A_{ul}}{4 \pi^2 c \Delta \lambda} N_{inv} \quad (4)$$

while $\Delta \lambda$ is the linewidth of the transition as determined by Stark broadening and the inversion density

$$N_{inv} \equiv N_u - N_l \frac{g_u}{g_l} \quad (5)$$

with g_j the statistical weight of level j . Estimating N_u by assuming each recombination event flows through that level and taking spontaneous emission as the dominant drain, we have

$$N_u A_{ul} = n_e \alpha_{rec} n_{Str}$$

with n_{Str} the density of fully-stripped ions. Estimating $N_{inv} = N_u / 2$ and $n_{Str} = n_e / 2Z$ we arrive at

$$\kappa = \frac{\lambda_{ul}^4}{16 \pi^2 c} \frac{n_e^2 \alpha_{rec}}{\Delta \lambda} \quad (6)$$

The Balmer alpha transition wavelength in Aluminum is $\lambda_{32} = 3.9$ nm. Using $n_e = 8 \cdot 10^{21} \text{ cm}^{-3}$, $n_e \alpha_{\text{rec}} = 4 \cdot 10^{11} \text{ sec}^{-1}$ and $\Delta\lambda \approx 4 \cdot 10^{-3} \text{ nm}$, we obtain a very large gain coefficient of, $\kappa = 4 \cdot 10^4 \text{ cm}^{-1}$.

We will now discuss some elements of the target design for a laser of this type. In a recombination time τ_{rec} , an impulsively heated, freely expanding plasma foil expands to a thickness $\Delta = C_S \tau_{\text{rec}}$, where C_S is the sound speed determined by the electron temperature T_e immediately after heating. In experimental units, $C_S = 9.8 \cdot 10^6 (T_{100} Z/A)^{1/2} \text{ cm sec}^{-1}$ for a plasma consisting of ions of mass number A , net charge Z , and electrons of temperature T_{100} measured in units of 100 eV. Ideally, $T_e \sim 0.3 \cdot I_p$. Taking $T_{100} = 7$ for fully stripped Aluminum, and setting $Z/A = 1/2$, we have $C_S = 1.8 \cdot 10^7 \text{ cm sec}^{-1}$. For $\tau_{\text{rec}} = 2.5 \cdot 10^{-12} \text{ sec}$, we have $\Delta = 4.5 \cdot 10^{-5} \text{ cm}$. Assuming initially solid densities, which for fully stripped Al yields $n_{e,s} = 9 \cdot 10^{23} \text{ cm}^{-3}$, the requirement that $n_e < n_{e,q}$ yields an estimate for the thickness of the solid target

$$\Delta_S = \frac{n_{e,q}}{n_{e,s}} \Delta \text{ cm} , \quad (7)$$

which for our parameters yields $\Delta_S = 4 \cdot 10^{-7} \text{ cm}$. Given the areal density $n_{e,s} \Delta_S$ one can estimate the time to establish temperature homogeneity. The thermal relaxation time is, roughly $\tau_{\text{th}} \sim \Delta^2/D$, with the thermal diffusion constant $D = 3.2 \lambda_{ei} v_{Te}$ expressed in terms of the electron-ion mean free path λ_{ei} and the electron thermal speed v_{Te} . In terms of the temperature, T_{100} , the electron density $n_{e,22}$ (in units of 10^{22} cm^{-3}), Λ_3 (the Coulomb

logarithm divided by 3), and Z_{13} (the ion charge divided by 13), D can be written

$$D (\text{cm}^2 \text{sec}^{-1}) = 5.2 \cdot 10^2 \frac{T_{100}^{5/2}}{n_{e22} Z_{13} \Lambda_3} \quad (8)$$

We see that τ_{th} scales as $\Delta^2 n / T^{5/2}$. Using mass conservation, Eq. (7), and neglecting energy loss processes during expansion so that $T \propto n^{2/3}$, we have $\tau_{th} \propto n^{-8/3}$. Therefore, if $\tau_{th} < \tau_{rec}$ when $n_e = n_{e,q}$ temperature homogeneity will be maintained for all earlier times. Taking $T_{100} = 2.3$, $n_{22} = .8$, $\lambda_3 = 1$, and $\Delta = 4.5 \cdot 10^{-5}$, we have $\tau_{th} = 3.9 \cdot 10^{-13} \text{ sec} \ll \tau_{rec}$, so that to a good approximation, $T_e(x,t) = T_e(t)$ during the relevant phase of foil expansion.

We now note the importance of the role a prepulse which, as we have seen experimentally, significantly affects the laser-target interaction. In the approach described above, large temporal and spatial gradients are prerequisites for inversion between levels which decay via allowed transitions. This is the principal rationale for development of fsec pumping systems. In order to develop the required level of contrast between the pulse energy and the prepulse energy ($\sim 10^4$), techniques such as spatial filtering and the use of saturable absorbers are not generally adequate. We propose the development of a "plasma saturable absorber" based on a thin film in a spatial filter configuration placed after the final amplifier. Preliminary calculations show the required contrast is achievable with a single stage absorber.

The second line of attack toward short wavelength x-ray lasers is to consider novel pumping schemes within the "two-laser" approach. Currently available technology makes possible the generation of extremely intense, short pulses of electromagnetic energy in the visible and ultraviolet. The electric field in such a pulse can exceed the binding field seen by at least the outer electrons of an atom - they become comparable at an intensity of 10^{16} W cm^{-2} - resulting in their rapid removal. The physics of the interaction of the field with the remaining, more tightly bound electrons is a subject of intense investigation here and elsewhere. Because the applied field strength is finite (albeit small) compared to the binding field, standard perturbative methods of quantum mechanics have limited applicability. On the other hand, the interesting regime is one in which the photon energy is small compared to the excitation and ionization energies of the ion. Therefore, the field-atom interaction occurs through the simultaneous transfer of many photons between them. We have been and will continue to investigate the 'multiphoton' interaction between fields and atomic and ionic systems of increasing complexity.

Initial amongst these has been the selective multiphoton excitation of the upper level of a proposed lasing transition involving either doubly excited states or inner-shell excitation. We have studied the multiphoton excitation of model two-level systems^{40,41} by preying on the relative smallness of the photon energy (i.e., frequency). Viewed from this perspective, the excitation/ionization problem has many similarities with the calculation of the breaking of adiabatic invariants of motion, a problem of widespread interest in plasma physics. Our current consensus is that the high order (i.e., many

photon) resonance involved in the selective excitation of an x-ray transition by ultraviolet photons is likely to be very narrow and very difficult to achieve experimentally. However, the tendency of atoms and ions to "adjust" their levels in the presence of a strong laser field (such as in the case of above threshold ionization) may help in reaching such resonances.

Finally, another possibility, under preliminary investigation, is the further multiphoton ionization of a partially-ionized ion without concomitant heating of the free-electron population.⁴² This should provide ideal conditions for subsequent recombination-pumped gain.

In order to quantify the field strength needed to achieve ionization in a many-electron ion, we have analyzed a Thomas-Fermi ionic model.⁴³ Because of the similarity scaling of the model with nuclear charge Z , we are able to derive a single universal curve of intensity required to ionize a particular charge state as a function of the ionization potential of that charge state. Application of the model to Xe, Kr, and Ar yield results in good agreement with recent experimental results^{44,45} on nonresonant multiphoton ionization.

6. Conclusions and Summary

A high power, short pulse ultraviolet laser system has been constructed and initial tests performed. In the future this system will be used as a pump source in a two-laser approach experiment to produce short wavelength (down to 1 nm) x-ray lasing. Laser-target interaction studies using the first stage of the system indicate that with careful reduction of prepulse energy and

appropriate target materials, these systems could also be applied to the production of high energy, flash x-ray sources. Such sources could be used to produce shorter wavelength x-ray lasing. Analysis of the effect of the prepulse on plasma generation shows that the hottest plasma condition occurred with minimal prepulse energy. Using layered targets, it was further shown that target thicknesses of $\leq 150\text{\AA}$ were involved in the generation of this hot plasma. Careful adjustment of prepulse conditions may, however, be useful in investigating the effect of the interaction of the extremely high electric field of the laser pulse with appropriately selected line emission.

Two approaches toward achieving lasing action at 1 - 5 nm were discussed. One relies on scaling successful recombination pumped laser experiments. The other uses the electric field of a powerful subpicosecond laser either to directly excite the upper lasing transition or to create a super-ionized plasma which then achieves lasing conditions during subsequent recombination.

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Figure Captions

- Fig. 1 Schematic representation of elements of the Two-Laser Approach experiment to produce short wavelength x-ray lasing.
- Fig. 2 Block diagram of the PSP-Laser System.
- Fig. 3 Autocorrelation traces of output pulses from stage 1 of the PSP-Laser with pulse compression system in place.
- Fig. 4. Experimental arrangement for the measurement of the effect of prepulse on plasma generation.
- Fig. 5 Schematic (not to scale) showing the variation of the amount and duration of prepulse energy with injection timing of the picosecond pulse.
- Fig. 6 Fluorine and carbon spectra obtained from the interaction of stage 1 of the PSP-laser with a teflon target. Injection timing, t , of the picosecond pulse is varied in order to vary prepulse energy.
a) $t = -3$ ns (weak prepulse), b) $t = 0$ ns (stronger prepulse) and c) $t = +3$ ns (strongest prepulse).
- Fig. 7 Reference spectra for interpretation of layered target interaction taken for PSP-laser interaction with a) solid Al target and b) solid Fe target.
- Fig. 8 Spectra taken from PP-laser interaction with layered targets (150Å of Fe on Al substrate) using different amounts of prepulse
a) strong prepulse (injection timing = -1.5 ns) and
b) weak prepulse (injection timing = -3.0 ns).

Table Captions

Table 1 Estimates of plasma parameters when a) $t = -3$ ns and b) $t = 0$ ns
 L is the thickness of the plasma; V_{exp} is the expansion velocity;
and Z_x is the average ionization stage of ion "x".

**New Xray Laser
System Block Diagram**

Fig. 1

Fig. 2

COMPRESSED PULSES

Output from KrF Amp II of PP-laser
(Two photon fluorescence technique in Xe)

Fig. 3

Fig. 4

SCHEMATIC REPRESENTATION OF VARIATION OF
PREPULSE WITH INJECTION TIMING

Fig. 5

Fig. 6

Fig. 7

Fig. 8

TABLE 1 : Evolution of Plasma Parameters for Weak and Strong Prepulse

a) weak prepulse, injection time $t = -3$ ns

N_e (cm ⁻³)	10^{23}	2×10^{22}	4×10^{21}
T_e (eV)	300	130	45
L (μ m)	0.05	0.2	1.0
V_{exp} (cm/s)	0.5×10^7	3×10^7	4×10^7
Ionization stage	$Z_F = 7.5$ $Z_C = 6$	$Z_F = 6.5$ $Z_C = 4.5$	$Z_F = 6$ $Z_C = 3.5$

b) strong prepulse, injection time $t = 0$ nsec

N_e (cm ⁻³)	10^{23}	2×10^{22}	4×10^{21}
T_e (eV)	—	130	60
L (μ m)	0.13	0.5	1.6

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