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Feasibility of a Laboratory X-Ray Laser Pumped by Ultrashort UV Laser Pulses

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Abstract. In order to allow widespread application of soft X-ray lasers there is a strong effort worldwide to use as small as possible pump lasers for plasma production. Short pulse lasers ($\tau \approx 1$ ps), particularly in the UV, have attracted much interest, since extremely high intensities (up to 10^{18} W/cm^2) can be achieved with a relatively high repetition rate. In this article we discuss their merit for soft X-ray laser pumping and possible solutions to the specific problems, for instance pulse front distortion, nonlinear absorption in window materials, plasma formation by short laser pulses and the relatively low total pump energy.

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Laser-produced plasmas still appear to be the only suitable medium for laser action below 250 Å. To generate population inversion on ionic transitions with an energy of more than 50 eV a high plasma temperature is necessary, which until now has been achieved by long-pulse high energy pump lasers. Unfortunately, these lasers are huge single-shot devices, and the overall efficiency is very low.

Despite the fundamental limitations regarding, e.g., the efficiency, considerable effort is being expended worldwide to realize an X-ray laser as a small laboratory device. There is little doubt that widespread applications will only become possible if the requirements concerning the pump laser dimensions can be relaxed and the repetition rate can be increased to, say, 1 Hz. A promising approach to high-intensity target irradiation employs the extremely high optical power nowadays available with ps or even sub-ps laser pulses, particularly in the ultraviolet [1–5]. However, present short-pulse (< 10 ps) laser systems produce at most a few Joules of optical energy compared to the mostly more than 100 J of pump energy employed in successful X-ray laser experiments so far [6]. As a consequence of the small pulse energy, an efficient focussing geometry is required. In particular, a travelling-wave pump arrangement may be advantageous, as has already been pointed out early [7]. Whereas effective multi-photon ionization in collisionless plasmas [8] and high-order frequency multiplication down to 146 Å [9] have been demonstrated by ps UV pulses, no successful X-ray laser experiment has been reported using them as pump pulses.

A few years ago the Laser Physics Group at the Max-Planck-Institut für biophysikalische Chemie, Göttingen, started to develop a short pulse UV laser system on a laboratory scale for potential application to X-ray laser pumping. In this paper we summarize the results that have been obtained concerning short pulse generation, amplification, and target experiments. Pulse propagation in optical materials has been studied in detail and will be discussed together with the consequences for suitable target geometries. The final section will be about laser-plasma interaction of ultrashort UV laser pulses and possibly applicable X-ray laser pumping schemes.

1. Short Pulse Generation

For the generation of sub-ps UV pulses we employ a hybrid excimer-dye laser system, of which the essential part is a short (80 μm) distributed feedback dye laser

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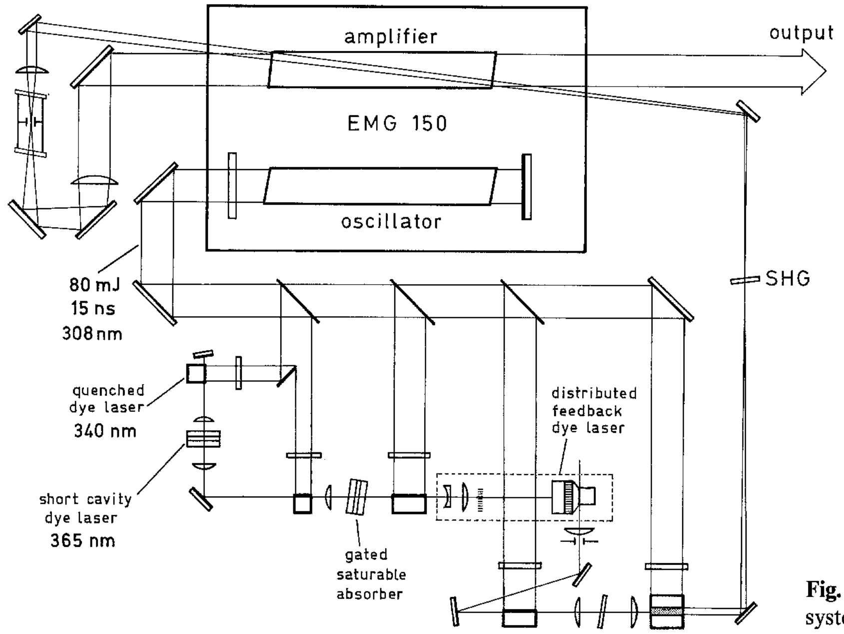

Fig. 1. Schematic of the sub-ps UV pulse system [Ref. 10; Fig. 1]

(DFDL) operating at twice the KrF wavelength (Fig. 1) [10, 11]. The oscillator tube of a dual-discharge excimer laser (Lambda Physik, EMG 150) at 308 nm pumps various stages of a cascade of dye lasers and amplifiers. The output of this consists typically of a broadband, ≈8 ps long pulse centered at 365 nm. The interference fringes for the DFDL are generated by imaging a transmission grating (55 l/mm) illuminated by this pulse into a dye cell, using a microscope objective. This set-up also allows easy tuning. It produces pulses of high spectral and temporal quality with small shot-to-shot fluctuation.

The sub-ps dye laser pulse is amplified, frequency doubled and sent twice through the amplifier tube of the EMG 150 filled with KrF. After the first pass the beam is spatially filtered. The output pulse has a typical energy of 10 mJ and a cross-section of $11 \times 25\ \mathrm{mm}^2$ [10].

2. Short Pulse Propagation and Amplification

The specific difficulties of short UV pulse generation of high intensity are, for instance, temporal pulse distortion due to dispersion and group velocity dispersion, suppression of ASE background, nonlinear absorption in optical elements, and suitable amplifier modules. In the following we briefly review these problems and possible solutions.

In general, the UV pulses have a significant chirp which is mainly introduced by the effect of group velocity dispersion and self-phase modulation in the optical elements. The first of these effects occurs if the second derivative $d^2n/d\lambda^2$ of the refractive index n with respect to the wavelength λ is nonvanishing. As a consequence, the pulses are longer than the transform-limit corresponding to the spectral bandwidth. The chirp can be compensated by, e.g., a pair of prisms, and the output pulse of the system described above can be compressed from typically a few hundred fs without any compensation to ≈60 fs [10].

Besides temporal distortion, the pulses also suffer pulse front distortion in dispersive optical elements. This effect is related to the first derivative $dn/d\lambda$ and can be used for the production of tilted wavefronts for transverse travelling wave excitation of dye lasers with short pump pulses [12]. However, the consequences of focussing short pulses were not recognized for a long time.

Since the group velocity of KrF pulses in common optical materials is significantly smaller than the phase velocity, a ray which has a longer path through the dispersive material is delayed with respect to a marginal ray (Fig. 2). Consequently, the pulse appears to be stretched in the focus of a convex lens [13–15]. This effect can also be compensated, for instance by means of an achromatic lens [14].

A lens system can be simultaneously compensated for both pulse front distortion and group velocity dispersion if the center wavelength is sufficiently far away from any absorption edge [14], since $dn/d\lambda$ and $\lambda d^2n/d\lambda^2$ are almost proportional [50]. The compensation has to take all optical elements into account including the focussing optics for target experiments. In order to avoid high power damage problems this compensation element is preferably positioned before the last amplifier.

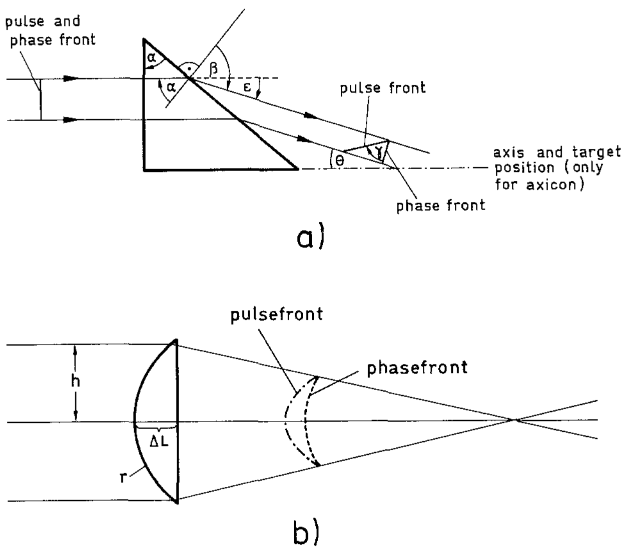

Fig. 2a, b. Pulse front distortion by a prism (or axicon) (**a**) and a convex lens (**b**). The sign of the angles is defined following usual mathematical convention

A problem which has not occurred until the availability of TW pulses in the UV is nonlinear absorption of common window materials [10, 16–18], which is mostly due to excitation of electrons from the filled conduction band into the empty valence band by KrF photons, each of 5.0 eV. Whereas the band gap is about 7.8 eV in fused silica, it is 10.0 eV in CaF_2 and even more in LiF and MgF_2 [16] leading to a much less severe absorption in fluoride crystals. However, LiF and MgF_2 are problematic window materials because of brittleness and birefringence, respectively.

CaF_2 thus appears to be most attractive. However, the high intensity behaviour of this material is critically dependent on the sample quality. The coefficient β of two-photon absorption ($dI/dz = -\beta \cdot I^2$) has been reported by one group to be 8.3×10^{-11} cm/W in CaF_2 [16] (z denotes the direction of propagation). Later measurements showed three-photon absorption with a corresponding coefficient γ ($dI/dz = -\gamma \cdot I^3$) of 2×10^{-21} cm^3/W^2 [18] and 3.9×10^{-23} cm^3/W^2 [17].

An important task for the generation of intense pulses is the suppression of Amplified Spontaneous Emission (ASE) in the amplifiers. First, ASE from one part of the system may deplete the inversion in the subsequent parts and second, no clean experiments on the interaction of the laser light with atoms or plasmas can be performed if the ASE background is above the threshold for ionization or plasma formation.

ASE is suppressed to a large extent by the use of spatial filters between the amplifier stages. Saturable absorbers, which are widely used in the visible, are still not available with convincing performance for UV radiation [19]. To reduce the ASE background it is advantageous to saturate only the last amplifier while leaving the earlier stage(s) in or slightly above the small signal gain regime. Using a commercial EMG 150 laser as an amplifier in a double pass arrangement, 10 mJ can be achieved in about 100 fs with a low ASE background of $\approx 6\%$ energy [10], but after further amplification to only ≈ 100 mJ with an EMG 401 (cross-section $\approx 2.5 \times 4.5$ cm^2) ASE is not negligible since the focussed intensity reaches the threshold for plasma production [5, 20].

For further energy scaling the beam has to be expanded to a wider aperture. Only the use of the complete gain spectrum of a highly saturated excimer medium allows the generation of sub-ps pulses [21]. An amplifier thus can produce a few times the saturation energy density which is 2 mJ/cm^2 for KrF (0.9 mJ/cm^2 for XeCl) (for sub-pulses) [22]. The difference between the two excimers is mainly due to the different ground state kinetics [22].

The construction of large aperture excimer amplifiers, which can be pumped either by a gas discharge or by a high energy electron beam, imposes problems of high voltage engineering and leads in general to less beam homogeneity and relatively small gain due to reduced pumping rate per unit volume. Discharge-pumped lasers offer a higher repetition rate, but they are still far from being realized for such large apertures as electron beam devices. We decided in favor of discharge-pumped technology: a 6×6 cm^2 laser has been built and studied [23]; a 10×10 cm^2 device with a scheduled repetition rate of 1 Hz (which, at present, appears to be the limit of the discharge technology) is under construction.

3. Focussing Optics and Target Geometry

To achieve a high laser intensity on a target, suitable focussing optics is as important as a large aperture amplifier. Depending on the experiment it should produce either a point focus (as often used in multiphoton absorption studies) or, as is preferable for X-ray laser studies, a line focus. In previous X-ray laser experiments a several mm long plasma is simultaneously excited by using a cylindrical lens [6] or an off-axis spherical mirror [24]. For reasons which will be discussed later, our approach essentially comprises travelling-wave excitation.

A possible realization of this idea consists of a quartz cone which is coaxially arranged with the UV laser beam axis [25]. If dispersion is not considered, it produces a point focus moving along the target on the axis of the cone (Fig. 2a) with a speed of

$$v = c/\cos\theta \tag{1}$$

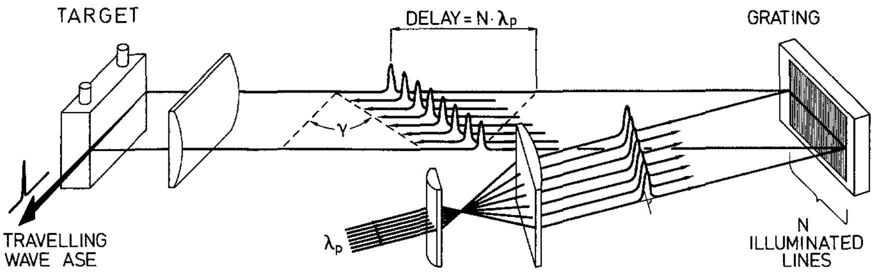

Fig. 3. Production of tilted wavefronts by a diffraction grating and schematic position of a target for travelling wave excitation; from [12]

(α is the base angle of the cone, $\sin\beta = n\sin\alpha$ and $\theta = \beta - \alpha$ is the grazing angle), which is faster than c, the speed of light in vacuum. Moreover, accounting for dispersion, the pulse front is tilted with respect to the direction of propagation. Since the pulse front includes an angle γ with the phase front, the speed of excitation along the axis will be even larger, namely (Fig. 2a)

$$v = c/(\cos\theta - \sin\theta\tan\gamma), \tag{2}$$

where

$$\tan\gamma = -\lambda\frac{d\varepsilon}{d\lambda} \quad [51]$$
$$= -\lambda\frac{dn}{d\lambda}\frac{\sin\alpha}{\cos\beta}. \tag{3}$$

$d\varepsilon/d\lambda$ is the angular dispersion (see Fig. 2a). For travelling-wave excitation v should be exactly matched to the velocity of the X-ray photons in the plasma which is derived from the plasma dispersion relation

$$n^2 = 1 - \frac{n_e e^2}{\varepsilon_0 m_e \omega^2}. \tag{4}$$

n_e denotes the electron density and ω the laser light frequency. The group velocity assumes the value

$$v_g = c\bigg/\left(n - \lambda\frac{dn}{d\lambda}\right) = nc. \tag{5}$$

To achieve a reasonable gain, a target length of several mm is necessary requiring a transit time of at least 10 ps. The mismatch due to (2) and (5) can be easily of the order of several ps. It may be compensated by a pair of CaF_2 axicons each having a convex lens instead of a flat base [26]. This arrangement, unfortunately, requires extremely precise manufacture and alignment.

An alternative approach to travelling-wave excitation with UV pulses is similar to the geometry used for dye laser pumping [12] and makes use of the above mentioned tilted wavefront due to the dispersion of a prism or grating (Fig. 3). If the incident beam includes a grazing angle θ with a target and the pulsefront is tilted in the opposite direction as in Fig. 2a (i.e., $\gamma > 0$), then speed matching can in general be achieved, however, possibly only under a small angle θ [27]; see (2). The development of a novel arrangement allowing pump-pulse compression and normal incidence of the pump beam for speed matching for the case of any target material is in progress [52].

If we consider the CVI laser at 182 Å, optimum amplification was observed at an electron density of about 10^{19} cm^{-3} [6]. Applying (5), we find a group velocity practically equal to c. Since an intense UV pulse would destroy a grating, the dispersive element has to be put at the front end of the amplifier chain. The line excited by the travelling wave can be imaged to the target line by suitable mirrors through the last amplifier. The travelling-wave scheme is preserved in this way, and the use of reflective optics provides a solution to the problem of non-linear absorption.

4. Short Pulse Laser Interaction with Matter

4.1. *Interaction with Gases*

Experiments of high intensity laser interaction with collisionless plasmas (i.e., dilute gases, in which the electrons ionized by the laser do not collide with ions within the time period of interest) have revealed the strong potential of short intense laser pulses for multiphoton ionization. Only a few mJ of a dye laser at 585 nm and 1–2 ps duration, focussed down to a few times 10^{14} W/cm^2 proved to be sufficient to produce Xe^{6+} ions, each of which requires 244 eV ionization energy [28]. Similar results were reported at comparable intensities with 20–100 fs short pulses at 620 nm yielding Xe^{3+} ions [29, 30]. By using UV radiation at 248 nm or 193 nm even Xe^{8+} ions were produced (10^{15}–10^{17} W/cm^2, 5 ps) [8, 9].

The ionization mechanism, however, is still not completely understood. At intensities above $\approx 10^{15}$ W/cm^2, the electric field strength of the laser field is comparable to atomic binding fields, and it is questionable whether perturbation theory is still applicable. In fact, the observed phenomenon of "above-threshold ionization" cannot be explained universally by application of perturbation theory. An early non-perturbative theory of high intensity laser-atom inter-

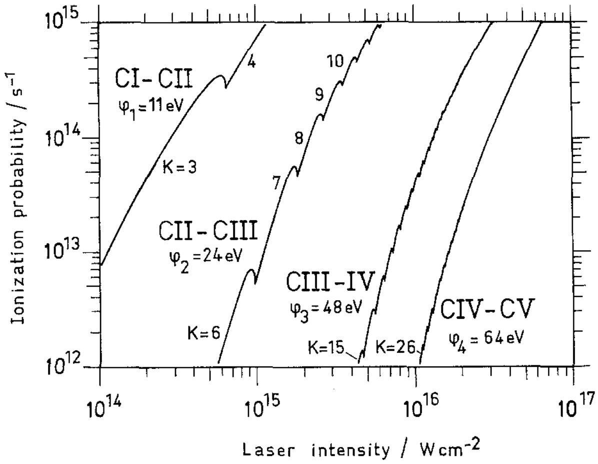

Fig. 4. Ionization probability of carbon atoms and ions calculated with the Keldysh theory. φ denotes the corresponding pure ionization potentials and K the number of absorbed KrF photons in the multiphoton picture

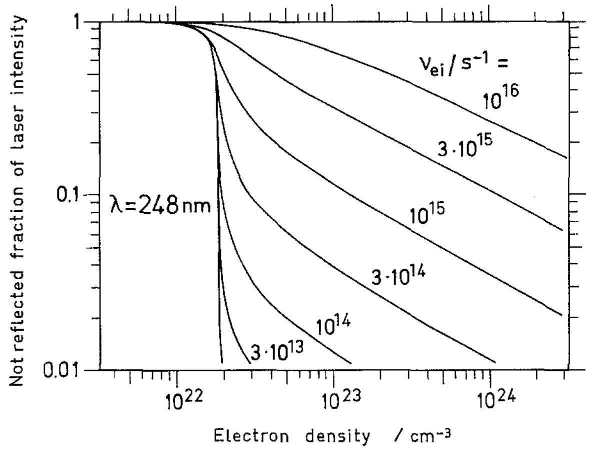

Fig. 5. Non-reflected fraction of KrF laser intensity incident on a conducting material (e.g., a plasma) with various collision frequencies ν_{ei} assuming an infinitely steep density profile

action by Keldysh [31], which provides a link between the classically opposite cases of field and multiphoton ionization, has attracted much interest [28, 29, 32]. The transition probability of a bound electron into a state in the ionization continuum is calculated in reasonable agreement with experimental results. The oscillation ("ponderomotive") energy of the newly freed electron in the laser field is considered; this already assumes a value of 60 eV for KrF radiation of 10^{16} W/cm^2 intensity and hence can no longer be neglected compared to the pure ionization energy. Figure 4 shows the transition probability of several ionization stages of carbon, calculated using this theory. It shows the extreme speed at which electrons are ionized provided their binding energy does not exceed, say, 50 eV [32]. The ponderomotive energy for longer laser wavelengths is larger, which is one reason for the more effective ionization by short wavelengths.

Carbon will thus be sequentially ionized to C^{4+} ions within ≈ 100 fs under the action of an intensity of 10^{17} W/cm^2 [33]. However, this multiphoton/field ionization only acts as plasma initiation, and more highly charged ions are formed by electron collisional ionization in the plasma.

4.2. Interaction of Short Laser Pulses with Plasmas

It is well known that laser light is most efficiently absorbed in the plasma region of near-critical density. Absorption by inverse bremsstrahlung (the effect of other processes like resonant absorption, etc. is more difficult to estimate and may not be as important for short pulses) is described by the complex index of refraction n,

$$n^2 = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \left[1 - i\frac{\nu_{ei}}{\omega}\right] \Big/ \left[1 + \left(\frac{\nu_{ei}}{\omega}\right)^2\right], \tag{6}$$

where ω denotes the light frequency,

$\omega_p = (n_e e^2/(\varepsilon_0 m_e))^{1/2}$

the plasma frequency, and ν_{ei} the electron-ion collision rate. $n_c = \omega^2 m_e \varepsilon_0 / e^2$ is the critical density.

If ν_{ei} is small compared to ω, practically no absorption takes place for $n_e > n_c$, whereas for $n_e < n_c$ practically all light enters the solid body. If ν_{ei} becomes comparable to the laser frequency ω, then absorption becomes also possible above the critical density (Fig. 5). If $n_e \gg n_c$ and $\nu_{ei} \ll \omega$, the absorbed (i.e., not reflected) fraction A of the incident energy can be estimated by

$$A \approx 2\nu_{ei}/\omega_p, \tag{7}$$

whereas the intensity absorption length α^{-1} is approximately

$$\alpha^{-1} \approx c/(2\omega_p), \tag{8}$$

which amounts to about 100 Å for $n_e = 10^{23}$ cm^{-3}.

For a fully ionized plasma (Lorentz gas), the collision frequency ν_{ei} depends strongly on the ion density, the effective ion charge and decreases with increasing electron temperature. With a reasonable value of 10^{15}/s [33], A assumes a value of 11%, which, under the given conditions ($n_e \gg n_c$), is only weakly wavelength dependent. It is expected that the collision frequency ν_{ei} increases with the intensity of the laser since the amplitude and the mean velocity of the free electron oscillation in the laser field become larger. Equations (7) and (8) are only valid for an infinitely steep density gradient. If the gradient length becomes comparable to the laser wavelength, effective ($\approx 100\%$) absorption takes place at the critical density surface. A treatment of light absorption in ultrashort scale length plasmas has been reported recently [34].

The first absorption experiments using KrF radiation [20] have shown that typically 50% of the laser energy (intensity 10^{14}–2.5×10^{15} W/cm^2, pulse length on target 250 fs) were absorbed under normal incidence. These results have been interpreted as absorption on a steep density gradient with a normalized collision frequency, ν_{ei}/ω, in the range of 0.1–0.15 in the critical density region.

Pulses have to be considered as short in this context if they are short compared to the time it takes the plasma to expand over one wavelength. Assuming an expansion velocity of $v_p = 5$ cm/μs [33] and $\lambda = 250$ nm, the critical expansion time becomes $t_c = 5$ ps. Plasma expansion hence leads to higher absorption until t_c is reached. This has been observed by monitoring the X-ray emission (which is a measure for the absorbed energy) from a plasma produced by two successive pulses of sub-ps duration [35, 36]. Using 620 nm laser radiation with 100 fs pulse length, the X-ray yield rises until the time delay is of the order of 50 ps [36]. A pre-plasma, formed by the ASE background or a pre-pulse may therefore be useful to allow higher coupling efficiency. However, the ASE duration (or temporal delay) should not exceed, say, 10 ps, because that may lead to distortion of the critical density surface.

4.3. The Use of Ultrashort UV Pulses

Radiation of extremely high intensity can only be produced with reasonable effort for a very short time, of the order of 1 ps. However, such short pulses offer also advantages. For instance, the expansion of the plasma leading to dilution can be neglected during the period of interaction. Even during 1 ps almost exclusively the electrons (i.e., not the ions) are heated up. Consequently, a higher electron temperature and stronger ionization of the atoms can be achieved [33]. The heating has to compete with increased nonlinear electronic heat conduction at high temperatures. However, only a region of ≈ 1 μm will be heated during 1 ps [32, 33]. Rapid cooling can start immediately after termination of the pulse, still at high electron density. Higher temperature, higher density and faster cooling are requirements for the scaling of present X-ray laser schemes towards higher Z [6].

The disadvantage of relatively small total pump energy may be compensated by a travelling-wave arrangement, which uses the laser pump energy most economically and becomes essential if the excited state lifetime is comparable to the laser pulse duration, and particularly in self-terminating transitions in order to generate a transient inversion.

The use of UV laser light is advantageous for at least three reasons: First, the availability of high power excimer amplifiers (which are among the few gain media capable of sub-ps pulses), second, the apparent higher performance in multiphoton absorption studies, and third, a relatively high critical plasma density. The critical density for KrF radiation is about 1.81×10^{22} cm^{-3}, which is not far below solid state density. The higher absorption density of UV radiation leads to higher collision rates in the plasma and may allow Z scaling in recombination schemes.

4.4. X-Ray Flash Generation by Short Laser Pulses

Besides collisional or recombination pumping, photopumping of inner-shells or resonant photopumping of optical transitions of ions are further approaches towards X-ray lasers. Successful experiments of inner-shell photopumping and lasing at about 80 nm have employed X-rays from laser-produced plasmas [37]. Until now, inner-shell lasers with shorter wavelength could not be demonstrated, and neither resonant photopumping has been successful in the soft X-ray regime. However, short X-ray bursts generated by ultrashort UV pulses may, besides photopumping of X-ray lasers, be used for ultrafast radiography or other applications.

Due to the high electron density (10^{23}–10^{24} cm^{-3}) local thermodynamic equilibrium is rapidly established. Applying standard formulas of plasma physics [38] it is seen that typical time constants of electron collisional ionization are of the order of 1 fs at these densities, which is much shorter than the laser pulse under consideration. Local thermodynamic equilibrium is accompanied by black-body radiation in the soft X-ray regime which may be used as a flashlamp for various applications. If we assume that the total intensity of the black-body radiation is comparable to the laser input intensity, the plasma temperature achieved by a laser intensity of 10^{15} W/cm^2 is estimated by the Stefan-Boltzmann law to be about 3 million degrees ($= 314$ eV).

This interaction produces a quickly rising X-ray flash caused by continuous and line radiation in the plasma [39]. A detailed collisional-radiative model which also considers absorption by inverse bremsstrahlung and nonlinear electronic heat conduction [32] showed that irradiation of a solid carbon target with 248 nm light of 10^{16} W/cm^2 (FWHM 300 fs) already leads to the formation of a considerable percentage (20%) of fully stripped carbon ions in a layer of ≈ 0.3 μm and to recombination radiation in the 400 eV regime following the laser pulse nearly instantaneously with an intensity conversion efficiency of about 1%. However, the trailing edge of the X-ray pulse is not so short, because it is determined by the cooling rate of the plasma due to adiabatic expansion and heat conduction/radiation. Since the more highly charged ions with the higher line transition energies recombine first, radiation with higher energy obviously ceases first. This has been established by X-ray streak camera measurements [40–42]. It was also shown that the X-ray pulse duration in the energy range above 1 keV is apparently limited by the time resolution of the streak camera ($\approx$20–30 ps) [40, 42]. Line radiation following complete ionization of C atoms, for which about 1 keV ionization energy per atom is required, was observed by focussing only 10 mJ KrF radiation to an intensity of 4×10^{15} W/cm^2 [40].

5. Possible X-Ray Laser Schemes

Estimates for the required pump sources for X-ray lasers generally consider the pump intensity. A typical value [43] is 10^{11} W/cm^2 for $\lambda = 100$ Å, and a scaling with λ^{-4}–λ^{-5}, depending on the mechanism of line broadening, is expected [6]. As far as the pump power is concerned the necessary value is easily reached by high power lasers. However, present X-ray laser schemes require a certain pump energy density for plasma heating. Direct pumping of inner-shell or ionic optical transitions by resonant multiphoton excitation has been discussed [44], however, convincing experimental evidence is still missing.

As realistic X-ray laser pumping schemes, there are the electron collision scheme, which has proved to work down to 65.8 Å in Eu^{35+} [45], and the recombination scheme in H-like ions, which has recently resulted in a 81 Å laser in F^{8+} [46]. Both schemes require a higher pump intensity for further wavelength scaling into the water window below 44 Å. Because of its relatively high efficiency [6] the recombination scheme appears to be most attractive.

A comprehensive model of recombining H-like plasmas cooled by adiabatic expansion was developed by Pert [47]. Scaling laws were derived for the required electron density ($n_e \propto Z^7$), temperature ($T_e \propto Z^2$) etc. for highest gain on the $n = 3 \rightarrow 2$ transition as a function of the ion charge Z. The optimum values for n_e and T_e are dictated by those conditions at which the upper laser level is dominantly populated by electron collisions, but the lower one is not (i.e., the "collision limit" is not below the principal quantum number $n = 3$). For the C^{5+} laser at 182 Å the corresponding experimental parameters were $n_e \approx 10^{19}$ cm^{-3} and $T_e \approx 20$ eV which resulted by cooling from initially 500 eV and $n_e \approx 10^{21}$ cm^{-3} [6]. The initial density is mainly determined by the pump laser wavelength through the critical density, whereas the temperature has to be sufficiently high to ionize the atoms completely.

Let us estimate roughly what is required to repeat the carbon experiments with short UV pulses. The main difference to long pulse pumping is that plasma heating is restricted to a much smaller region given by the range of the electronic heat wave of approximately 1 μm within 1 ps [32, 33]. At the critical density of KrF ($n_c = 1.81 \times 10^{22}$ cm^{-3}) the minimum temperature to generate a relative C^{6+} ion concentration of 99% is about 200 eV, as calculated by the Saha equations. Taking only ionization energies and electronic heat ($= 3n_e kT_e/2$) into account (the ions are not heated within 1 ps) this corresponds to an energy of 3 keV/atom or 1.5×10^6 J/cm^3. If we assume a heated depth of 1 μm, a focal line width of 10 μm and a target length of 1 cm, this corresponds to 150 mJ absorbed laser energy and 3×10^{14} C^{6+} ions. Although this pulse energy is available with present short-pulse UV lasers they do not appear to be best suited to the carbon laser, since the density has to drop by three orders of magnitude from absorption to X-ray lasing.

For higher Z materials the density for maximum gain is higher, so it does not have to drop as far from the initial absorption density. For an X-ray laser in the water window Al^{13+} is a candidate using this scheme, and the necessary temperature at $n_c = 1.81 \times 10^{22}$ cm^{-3} is about 600 eV corresponding to 18.3 keV/atom and 4×10^6 J/cm^3. For the same experimental conditions as above, these are equivalent to 400 mJ of absorbed laser energy and 1.4×10^{14} bare aluminum ions. Z scaling apparently does not dramatically increase the demand for pump pulse energy but also leads to a smaller number of fully ionized atoms able to form H-like ions by recombination. Even the pulse energy required for the Al laser does not appear to be out of range for present UV lasers. The maximum X-ray laser energy (i.e., when each H-like aluminum ion produces one laser photon) is not more than 7 mJ, and will more likely be of the order of a few μJ.

The creation of a $3 \rightarrow 2$-inversion in hydrogen-like ions does not take advantage of the travelling-wave approach, since the time lag between pumping and lasing will be considerably larger than the UV pump laser length. However, the kinetics in hydrogen-like ions also allow inversion by recombination on the $2 \rightarrow 1$ transition [48]. Here, lasing takes place at higher density, and the collision limit is at about $n = 2$. Recently, this proposal has attracted renewed attention [49]. The idea is to create a relatively cold plasma (i.e., produce electrons with a small excess kinetic energy) by selective multiphoton ionization to allow rapid recombination. It was shown that, for instance, transient inversion on the self-terminating $2 \rightarrow 1$-transition in hydrogen-like carbon ions can be accomplished at an electron density of 10^{21}–10^{22} cm^{-3} using pulses of 100–200 fs length. These parameters appear to be well suited to the short UV pulse approach. If this scheme proves to be viable it will be an ideal application for short-pulse lasers because it is likely to allow higher pumping efficiency than with hot plasmas.

6. Conclusion

We have discussed the prospects of the high-intensity, short-pulse approach to X-ray laser pumping, in particular with KrF lasers. The relatively low total pulse energy is the main drawback of this idea, and a considerable increase in this would destroy the basic idea of improved repetition rate and small scale experiment. Hence, there must be particular emphasis on an efficient target geometry and effective coupling of the optical energy into the plasma. Travelling-wave arrangements and formation of a plasma by a prepulse appear to be attractive. Recombination schemes are most promising because of their relatively high efficiency. In particular, the necessary UV laser pump energy seems to be attainable for the $3 \rightarrow 2$- and the self-terminating $2 \rightarrow 1$-transition in hydrogen-like ions.

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