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ADVANCED DESIGN AND MODELING CONCEPTS FOR RECOMBINATION X-RAY LASERS

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Advanced design and modeling concepts for recombination x-ray lasers

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Abstract. Geometric, kinetic, and trapping issues, in short and ultrashort recombination x-ray lasers, are discussed. The design of a composite target consisting of a lasant strip on a plastic backing is described. Examples of modeling showing the effect of photon trapping and uncertainties in other physical processes on calculated gain coefficients are given. A simple and accurate expression for photon trapping in cylindrical geometry is presented. Recombination lasers that have the ground state as the lower laser state are shown to have small I_{sat}'s and corresponding low efficiencies. Scaling laws for femtosecond laser-plasma interactions are presented.

1. Introduction

Two major approaches to x-ray lasing are collisional excitation in Ne- or Ni-like ions and recombination into H- or Li-like ions. Recombination schemes generally use higher intensities, but less total energy than collisional schemes. Many of the lasers that have been used to drive x-ray lasers are designed for long-pulse operation (ICF drivers) and, being power limited, cannot benefit from the reduced energy requirements of recombination schemes. In addition, most recombination x-ray laser experiments have obtained relatively small gain length products. Recombination x-ray lasers are a viable alternative to collisional schemes but require drivers with high intensity, short pulse and narrow focusing capabilities. Target designs depend on the characteristics of the driving laser.

An idealized target geometry for a recombination x-ray laser is a free-standing narrow exploding-strip of lasant material. The vertical height of the strip is chosen to match the horizontal expansion size when the driving laser shuts off, giving mainly 1-D expansion of the strip during the heating phase followed by 2-D expansion during the cooling phase. For a free-standing strip, the height of the laser focus has only a small effect on gain provided that the laser illuminates the whole strip. In practice, the strips must be supported and in this case, the height of the laser focus can be important in determining the gain. We show the effect of supporting the lasant strip on a thin plastic backing.

A target geometry that has had experimental success is an ablating fiber. The fiber is supported at one end and the maximum length is limited by bending of the fiber. Experiments are being conducted at Rutherford-Appleton Laboratory where the free end of the fiber is supported electrostatically, allowing longer lengths. As for free-standing strips, the predicted gains do not depend critically on the size of the laser focus. A disadvantage of the fiber geometry is that maximum gain often occurs in regions with steep gradients in electron density and refraction can be a problem. We present modeling results for fibers coated with LiF and Al.

In every demonstrated x-ray lasing scheme, the lower lasing level is emptied by a fast radiative transition to the ground state. The probability that these photons escape the plasma can have a large effect on the predicted gain coefficients. If the velocity field has steep velocity gradients (which is the case for exploding and ablating targets), one can use escape probabilities to account for the effects of photon trapping (Eder 1989). We give a very simple but accurate expression for the escape probability in cylindrical geometry. The expression can be used for both recombination and collisional schemes. It has been conjectured that trapping is overestimated in the modeling of recombination experiments (Pert and Rose 1990). We discuss a proposed physical justification for reducing trapping and also discuss how uncertainties in other processes, such as the equation of state, can affect the gains predicted by modeling.

For all the recombination schemes discussed above, collisional ionization by thermal electrons is the dominant ionization mechanism. There are proposed recombination schemes that use very high intensities but ultrashort pulses (≤ 1 ps) lasers where optical-field-induced ionization is the dominant mechanism (Burnett and Corkum 1989). The potential advantage of these schemes is the possibility of short wavelengths by lasing into the ground state of the ion. We show that a disadvantage of the lower state being a ground state is a small $I_{\rm sat}$ leading to low output energies.

Ultrashort-pulse optical/UV lasers can also be used to create a short pulse of incoherent x-rays to be used in a variety of applications. We present scaling laws for the efficiency of x-ray production using femtosecond pulses for Si and Yb targets.

In Section 2, we discuss the design of composite targets showing the effect of a thin plastic backing on the predicted gain coefficient. In addition, we discuss the role of photon trapping on both pure Mg and MgF_2 strips. In Section 3, we compare modeling results with observations for fibers coated with LiF and Al. In Section 4, we give a useful formula for photon trapping in cylindrical geometry. The effect of the lower state being a ground state on $I_{\rm sat}$ is presented in Section 5. In Section 6, scaling laws for ultrashort-pulse laser interactions are presented.

2. Recombination target design

Detailed design calculations for a H-like Mg recombination x-ray laser have been completed (Eder 1990). We summarize this design work showing that even a thin plastic backing can affect the predicted gains for a lasant strip supported by plastic. We discuss how including photon trapping has a different effect for Mg strips than for MgF_2 strips. General issues important in designing recombination x-ray lasers are discussed.

Our design effort for recombination x-ray lasers has concentrated on exploding strips that are free standing (not physically realizable) and ones supported on a plastic backing. The use of exploding strips as compared with exploding foils is desirable for two reasons. First, a narrow strip allows the possibility of 2-D expansion after the laser is off — even for a wide laser focus. This is of particular importance in designing recombination x-ray laser targets for the Nova 2-beam laser with a line focus width of 100 μm (Campbell *et al* 1986). The second benefit of strips, even for a narrow laser focus, is the reduction of emission from cooler regions outside the laser focus. This emission makes the measurement of ionization balance and gain more difficult (Eder *et al* 1987).

The interaction of the driving laser with the target and the resulting hydrodynamic expansion is modeled using the simulation code LASNEX (Zimmerman and Kruer 1975). Modeling a composite target (lasant strip on a plastic backing) is greatly improved by using distinct grids for the strip and plastic regions with an independent number of horizontal and vertical zones. The different regions are still connected and energy passes through the boundaries between the regions. For a given plastic thickness, the effect of the plastic increases as the lasant strip is made thinner. In addition, the effect is larger as the strip gets narrower for a given thickness. The expansion of the plastic causes a channeling of the strip expansion affecting the outer portions the most. In a free-standing strip, these outer regions have the largest fractional expansion and therefore are the source of the majority of the expansion cooling which is transferred throughout the plasma. The result is that for the center of the lasant strip where gain is usually the largest, the density is not significantly affected by the plastic but the temperature decreases more slowly, leading to a reduction in the predicted gain coefficients.

The calculation of $n = 3$ to $n = 2$ gain coefficients in H-like Mg requires the use of atomic models in which the fine structure of these levels are taken into account. The $n = 3$ levels tend to be populated according to the statistical weight of the levels, but the $n = 2$ levels can deviate significantly. The dominant depopulating channels out of the $n = 2$ levels are the rapid dipole $2p_{3/2} - 1s_{1/2}$ and $2p_{1/2} - 1s_{1/2}$ transitions. This can result in the $2s$ level being over populated with respect to the $2p$ levels unless $\Delta n = 0$ collisions between the levels can restore the three levels to statistical equilibrium. We have found that if only electron collisions are included, the $2s$ level can have a significantly higher population than given by its statistical weight. Using an ion collision code (Walling and Weisheit 1988), we find that ion collisions have a small affect for connecting $2s$ and $2p_{3/2}$ levels ($\Delta E \approx 1$ eV) compared with electron collisions, but strongly connect the $2s$ level to the $2p_{1/2}$ level ($\Delta E \approx 0.03$ eV) with a rate about a factor of 20 larger than the electron collision rate. The connection of the $2p_{1/2}$ level to the $2s$ level by ion collisions increases the $2p_{1/2}$ population. Including ion collisions in the modeling increases the predicted gain coefficient for the $3d_{5/2} - 2p_{3/2}$ transition and decreases the predicted gain coefficient for the $3d_{3/2} - 2p_{1/2}$ transition. All the gain coefficients in this section are for the $3d_{5/2} - 2p_{3/2}$ transition. The population of the $2p_{3/2}$ level depends on whether the photon emitted from the $2p_{3/2} - 1s_{1/2}$ transition escapes the plasma or is absorbed and repopulates the $2p_{3/2}$ level. In Section 4, we discuss how the effects of photon trapping are including in our design and modeling calculations.

Table 1 shows the effect of the plastic backing on the gain for pure Mg and MgF_2 strips. The wavelength of the driving laser is taken to be 0.53 μm with a line focus height of 100 μm and a pulse duration of 20 ps. The peak values of the gain coefficient for the $3d_{5/2} - 2p_{3/2}$ line are given for a zone at the center of the expansion for untrapped and trapped calculations. For two sets of strip parameters (first and last), the effect of the plastic is small. In contrast, the thin ($W_s = 2000$ Å) and narrow ($H_s = 25$ μm) strip is affected by the plastic with the gain coefficient about 50% lower than for a free-standing strip. For untrapped calculations pure Mg targets have gain coefficients about 2.5 times that of MgF_2 targets. Trapping reduces the gain for both Mg and MgF_2 targets, but has a bigger effect for the pure Mg targets. This is due to the larger number of Mg ions which increases the optical depth of the $2p_{3/2} - 1s_{1/2}$ transition. Trapping is predicted to be more important for the thicker strips. The predicted gains in Table 1 are relatively small if the effects of photon trapping are included.

W_B (Å)	W_S (Å)	H_S (μm)	I (W/cm^2)	Mg UT (cm^{-1})	Mg T (cm^{-1})	MgF_2 UT (cm^{-1})	MgF_2 T (cm^{-1})
500	2000	50	4×10^{14}	4.0	0.3	1.6	0.7
0	2000	50	4×10^{14}	4.0	0.3	1.6	0.7
500	2000	25	4×10^{14}	4.2	0.7	1.7	0.8
0	2000	25	4×10^{14}	6.0	1.3	2.4	1.3
500	4000	25	8×10^{14}	9.4	0.4	3.6	0.7
0	4000	25	8×10^{14}	9.7	0.5	3.8	0.6

Table 1: Peak gain coefficients for the $3d_{5/2} - 2p_{3/2}$ transition. The first four columns specify the target conditions (width of plastic backing W_B, width of strip W_S, height of strip H_S, and the intensity on target per side I). The last four columns give the predicted gain coefficient for untrappped (UT) and trapped (T) Mg and MgF_2 strips.

Our modeling of various experiments, discussed in Section 3, suggests that the gains for targets discussed in this section might be larger than the trapped values in Table 1. If there are local velocity gradients that are much steeper than those calculated, the effect of trapping would be reduced and a value between the trapped and untrapped values would be expected. This possibility is discussed in more detail in Section 4. Another reason for the experimental gains to be larger than simulations is that the plasma cools more rapidly than predicted by the modeling. The recombination rate and gain depends strongly on the cooling rate. If the cooling rate is artificially increased by 10%, the target with a 25 μm high and 2000 Å wide strip on a plastic backing has gain coefficients of 8.1 cm^{-1}, 3.2 cm^{-1}, 3.2 cm^{-1}, and 2.6 cm^{-1} for untrapped Mg, trapped Mg, untrapped MgF_2, and trapped MgF_2 respectively. The untrapped values are about a factor of two larger than those in the table with an even larger effect for the trapped gains.

A major conclusion that comes from our design work is the importance of a narrow laser focus. We show that even a thin plastic backing can affect the predicted gain coefficients for strip targets if a wide laser focus is used. An optimum target/laser combination would consist of a 25 μm strip on a thin plastic backing illuminated by a laser with a 25 μm laser focus.

3. Modeling of recombination experiments

Lasing has been observed in H-like F (Grande *et al* 1990) and Li-like Al (Carillon *et al* 1990) using coated fiber targets. We summarize modeling results for these experiments and comment on H-like Na and H-like Mg experiments using exploding foils. In the modeling of the H-like F experiment (Eder 1989), we showed the effect of varying the flux limiter and the amount of resonance absorption on the predicted gain coefficient for the $3d_{5/2} - 2p_{3/2}$ transition. A maximum gain coefficient of 1.9 cm^{-1} is found for a flux limiter of 0.1 and 1% resonance absorption. The peak experimental value of 4.4 cm^{-1}, which involves spatial averaging, is more than a factor of two higher. Neglecting photon trapping in the modeling gives a maximum gain coefficient of 7 cm^{-1}. Artificially increasing the cooling rate in the modeling also causes a large increase in the predicted gain coefficient.

The observed gain coefficients for the Li-like Al fiber experiment are 2.5 cm^{-1} for the $3d-4f$ line and 1.5 cm^{-1} for the $3d-5f$ line. Our modeling of this experiment gives maximum gain coefficients of 0.2 and 0.01 cm^{-1} for the $3d-4f$ and $3d-5f$ transitions respectively. Neglecting photon trapping in the modeling gives peak values a factor of ten higher resulting in the $3d-4f$ value being within a factor of two but the $3d-5f$ still much less than observed. These untrapped results are consistent with modeling done by Klisnick *et al* (1990). The large disagreement for the $3d-5f$ line is enhanced if the line is Stark broadened.

Neglecting or reducing photon trapping generally gives better agreement between modeling and experiment. One idea to justify this approach is discussed in the next section. At this time, neglecting trapping is done only on empirical grounds. Artificially increasing the cooling rate by a relatively small amount can also increase the predicted gain coefficients resulting in better agreement between modeling and experiment. We discuss three ideas to justify an increased cooling rate. The first idea is the possibility that LASNEX underestimates the cooling of the expanding plasma through conduction to the cold fiber remnant. We increased the conduction in LASNEX between the remnant and the expanding plasma by a factor of five and observed no significant increase in cooling. Enhancing radiative cooling by a factor of five also gave no significant increase in cooling. The reason that increasing conduction or radiative cooling has a small effect is that cooling due to expansion is calculated to be the dominant mechanism. The third idea is to affect the expansion directly through the equation of state. If the pressure obtained from LASNEX's equation of state is increased, the plasma expands faster and cools more rapidly. We have found that a 25% increase in pressure results in enhanced cooling, leading to a factor of 2.5 increase in the predicted gain coefficients. This increase is less than the factor of 10 increase from neglecting trapping and would also have to be justified.

Lasing has been reported from $n = 3$ to $n = 2$ transitions in H-like Na at 54 Å (Azuma *et al* 1990) using a laser driver with a 28 ps pulse and a 30 μm wide laser line focus on foil targets. Modeling of this experiment also requires the neglect of trapping to achieve values comparable to the quoted gain coefficients of 4 cm^{-1}. Microdot experiments showed large population inversions for the $n = 3$ to $n = 2$ levels in H-like Mg using a 20 ps driver (Charatis *et al* 1990). Modeling of these experiments give reasonable agreement with respect to ionization balance but there are discrepancies between predicted density profiles and ones obtained from holographic interferograms (Eder *et al* 1989). The observed population inversions are between the calculated values with and without trapping. Preliminary results from Nova experiments, using a 20 ps pulse and a 100 μm wide laser line focus on foil targets, show much smaller population inversions for the $n = 3$ to $n = 2$ transitions in H-like Mg and no gain was observed. The smaller inversions are believed to be the result of slower cooling of the plasma in the line-focus as compared with the dot-focus geometry. There is no data for the composite targets discussed in Section 2.

4. Photon trapping

The velocity fields for lasant strips and ablating fibers have steep velocity gradients implying that escape probabilities can be used to calculate photon trapping. An additional simplification is possible if the expansion can be treated as cylindrically symmetric. This is a good approximation for free-standing strips late in the expansion when gains are the largest For composite targets, where there is channeling by the plastic, the velocity and the gradient of the velocity in the interior zones of the strips are almost equal in the horizontal and vertical direction at the time of maximum gain implying that a cylindrically symmetric expansion is a good approximation for these interior zones. For fibers with multiple beam illumination, the expansion in nearly cylindrically symmetric for the entire expansion. General expressions for the escape probability in cylindrical geometry have been recently derived (Shestakov and Eder 1989). We give a very simple but accurate expression for the escape probability

$$P_s = \frac{1}{3\tau} - \frac{2}{3}e^{-\tau}\left[\tau K_0(\tau) + \left(\frac{1}{2} - \tau\right) K_1(\tau)\right],$$

where $\tau = \xi/(v' + v/R)$, $\xi = hc/4\pi\,(N_i B_{ij} - N_j B_{ji})$, K_0 and K_1 are the modified Bessel functions, $N_{i(j)}$ are the ion densities and $B_{ij(ji)}$ are the Einstein stimulated emission and absorption coefficients. The above expression is accurate to 4% for $\alpha \leq 0.5$, where $\alpha = (v' - v/R)/(v' + v/R)$. This condition is almost always satisfied in regions that have gain. The expression is exact for expansions that are self-similar ($v' = v/R$). The above expression is more accurate and easier to calculate than others that have been used to calculate trapping in cylindrical geometry.

There is one potential difficulty in using escape probabilities in the case of multiple lines. This can arise among the fine-structure levels where one fine-structure line can absorb photons from a different fine-structure line due to bulk velocity differences between the emitting and absorbing regions. Recent calculations comparing line transfer results with escape probabilities show that for a group of interacting lines, the line with the highest energy is not significantly affected by the other lines (Eder and Scott 1990). This is because in a frame comoving with the expanding plasma all lines emitted from other regions of the plasma are redshifted with respect to a potential absorber. That means the lower energy $2p_{1/2} - 1s_{1/2}$ line can absorb photons emitted from the $2p_{3/2} - 1s_{1/2}$ line, but the converse does not occur. Because the $3d_{5/2} - 2p_{3/2}$ gain coefficient depends only indirectly on the population of the $2p_{1/2}$ level, the escape probability treatment should give good results provided that the usual requirement of having sufficiently steep velocity gradients is satisfied.

If the velocity gradient in the radial direction is very steep in some regions and shallow in others, there is the possibilty of having a larger spatially averaged gain than obtained from a self-similar expansion. In the regions of steep gradients, there is enhanced probability of escape and higher gain coefficients, which can more than compensate for the reduced gain in regions of shallow gradients. Lightbody and Pert (1990) have presented calculations for fiber targets with two-sided illumination showing that the velocity flow has vorticity structure superimposed on the radial expansion giving rise to regions of steep and shallow velocity gradients. The major questions to be answered include the alignments of these high gain regions, the volume of the regions, and the velocity fields for multiple beams on a fiber and for line focus on foil or strip targets.

5. I_{sat} for ground state lasers

The advent of ultrashort-pulse high-intensity lasers offers the possibility of short wavelengths by lasing into the ground state of the ion. High intensities are required to have optical-field-induced ionization which can "completely" empty the ground state and short pulses are required because the radiative rate connecting the upper laser state to the ground state is very rapid. The rates out of the ground state are comparatively slow resulting in the lasing terminating on this fast time scale of order 1 ps. Large small-signal gains are possible for such transitions provided that additional heating by plasma processes such as Raman can be kept at a minimum. We are investigating the importance of Raman heating. The purpose of this section is to show the importance of the lower lasing state being the ground state, through the effect on I_{sat}.

The saturated intensity is defined as the intensity that, through stimulated emission, causes the gain coefficient to be reduced by a factor of two. Define a constant α to be the ratio of the net stimulated emission to the total destruction rate out of the upper laser state without stimulated processes. The new population (including stimulated processes) of the upper state n'_u is given by $n'_u = \beta n_u$, where $\beta \equiv 1/(1+\alpha)$. The number of electrons, which are stimulated to have a transition to the ground state and accumulate there, depend on the number of high Rydberg levels that exist in the next lower ionization stage. We have found that at the densities required to achieve high gain, continuum lowering causes the maximum number of Rydberg levels to be of order 7 and the population in these upper levels can be neglected with respect to the ground state. In this case, the new population n'_l in the lower lasing level is $n'_l = n_l + (1-\beta)n_u$. The amount of stimulated emission, expressed through β, which causes the gain to be reduced by a factor of two is $\beta = [(1+n_l h_u/n_u h_l)/2 + h_u/h_l]/(1+h_u/h_l)$. The statistical weights of the levels can have a large affect on β. The inversion $(1-n_l h_u/n_u h_l)$ is usually between 0.25 and 0.5 at the time of maximum gain. For the $n=3$ to $n=2$ transition in H-like B at 48 Å with $h_u/h_l = 4$, these inversion values give $\alpha = 0.03 - 0.05$. The value of I_{sat} is proportional to α. The resulting small I_{sat} combined with the short duration of these lasers leads to relatively low efficiencies. We are investigating Li-like levels which have smaller ratios of statistical weights and longer wavelength systems to improve the efficiency.

6. Scaling laws for femtosecond interactions

Ultrashort-pulse optical/UV lasers can also be used to create a short pulse of incoherent x-rays to be used in applications such as inner shell photopumping of x-ray lasers. Scaling laws for the interaction of femtosecond pulses with solid and exploding-foil targets have been derived (Rosen 1990). We summarize a few of the results and show how the efficiency of x-ray production scales with input energy for Si (Z = 14) and Yb (Z = 70) targets.

During a laser pulse of duration 100 fs, it is a good approximation to neglect hydrodynamic motion. Assuming the laser energy is deposited in a skin depth at some constant absorption fraction, the temperature can be determined by balancing this incident energy with conduction to the cold interior. The temporal dependence of temperature for a flat-top pulse of duration t_0 is $T = T_0(t/t_0)^{2/9}$ for $t < t_0$, where $T_0 = C_T E^{4/9} t_0^{-2/9}$ and C_T is a constant. The temporal dependence of the scale length is $\ell = \ell_0(t/t_0)^{7/9}$ for $t < t_0$, where $\ell_0 = C_\ell E^{5/9} t_0^{2/9}$ and C_ℓ is a constant. Typically, ℓ is found to be much shorter than the radiation Planck mean free path λ implying that the region is optically thin. The plasma radiates approximately as a diluted black body $P_R \approx A\sigma T^4 \ell/\lambda$. For Si we find that $\lambda \approx 3 \times 10^{-5} T_{\rm heV}^{2.5}$ cm using the average atom model in LASNEX. Ytterbium has a different scaling given by $\lambda \approx 10^{-5} T_{\rm heV}$ cm. One finds that for Si and Yb, P_R scales with temperature to the 1.5 and 3.0 powers, respectively. These can be used to calculate the scaling of efficiency, η, with incident energy for Si, $\eta \sim E^{2/9}$, and for Yb, $\eta \sim E^{8/9}$. The faster scaling with temperature of λ for Yb contributes to the faster scaling with incident energy. Rosen (1990) also gives scalings including the effects of hydrodynamic motion and flux limiting as well as results for exploding foils that can be used to give shorter duration x-ray pulses.

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