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BY RADIATION LOSSES IN PLASMAS:
APPLICATION TO SOFT X-RAY LASER DEVELOPMENT

By

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A MODEL FOR ELECTRON COOLING BY RADIATION LOSSES IN PLASMAS:

APPLICATION TO SOFT X-RAY LASER DEVELOPMENT

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ABSTRACT

We present a simple model which may be used to evaluate the suitability of different ions for rapid plasma cooling by line radiation in recombination pumped X-ray laser schemes.

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There has been much interest recently in soft X-ray laser schemes based on fast radiation cooling of a recombining plasma. A gain-length product of 6.5 on the CVI 182 Å line was achieved at the Princeton Plasma Physics Laboratory in a recombining magnetically confined plasma column, with a factor of two increase in stimulated emission observed in initial experiments with soft X-ray mirrors.¹ At Lawrence Livermore National Laboratory, significant amplification² was obtained at 206 Å and 209 Å in neon-like selenium with a gain-length product of 6-7. The absence of the $J = 0$ to $J = 1$ transition at 183 Å, predicted by a collisional excitation model³ to have the highest gain, prompted Apruzese *et al.*⁴ to propose an alternative explanation of the Livermore results based on rapid radiative cooling in a recombining plasma. In an experiment at the University of Rochester,⁵ a gain of $\sim 3 \text{ cm}^{-1}$ was observed on the CVI 182 Å transition and interpreted in terms of radiation cooling by selenium; this has been supported recently by more detailed calculations.⁶

In recombination pumped X-ray laser schemes, a laser-produced plasma is cooled rapidly and the large influx of recombining ions into highly excited states together with rapid radiative depopulation of a lower excited state generates a population inversion. Rapid cooling of the plasma may be achieved by radiation losses. Typically, the faster the electron cooling is, the higher the population inversion and gain, provided the electron density is in the proper range. Some flexibility may be achieved by use of a two-component plasma where one ion species is chosen to provide the maximum radiation cooling while gain at the desired wavelength is generated in a second species. The total amount of radiation cooling increases with the density of the "coolant" ion. There is a limit, however, to the coolant density at the point where the additional plasma electrons associated with the coolant ions

increase the electron density to the point where electron collisions prevent any population inversion from developing in the gain medium. It is desirable to pick a coolant ion with the maximum electron cooling rate per ion for the plasma conditions appropriate for fast recombination. Constructing a detailed atomic model for the many candidate ions in order to compare their cooling properties is, however, a time-consuming task. We describe below a simple two-level model which addresses this problem.

We consider the following question: for a given plasma electron density and temperature, what is the optimal ion (i.e., ion with the optimal energy level structure) for maximizing the electron energy loss rate through excitation of line radiation? Kononov and Koshelev⁷ considered radiation cooling in dense aluminum plasmas and showed that ions of ground state configuration $1s^2 2s^n 2p^m$ with resonance transitions having an energy separation, ΔE , comparable to the electron temperature ($\Delta E = T_e$) could be effective coolants. We take a more general approach and consider a two-level model consisting of a ground level, g , and excited level, i . Electrons are cooled by electron collisional excitation, followed by radiative decay. Contributions to the excited state population, N_i , by recombination/cascade are not included in this model since, while they add to the total radiated power, they do not significantly increase the electron cooling rate. The excited state population N_i and electron cooling power K_{TOT} (erg cm⁻³ sec⁻¹) are given by

$$N_i = N_g N_e S / [A + N_e S \exp(\Delta E / T_e)], \quad (1)$$

$$K_{TOT} = N_i A \Delta E = N_g N_e S A \Delta E / [A + N_e S \exp(\Delta E / T_e)]. \quad (2)$$

Here N_g is the ground level population, N_e the electron density, λ the radiative decay rate, ΔE the energy level separation, and S the collisional excitation rate. We use the following expression⁸ for the collisional excitation rate for dipole allowed transitions:

$$S = 1.6 \times 10^{-5} f \bar{g} \exp(-\Delta E/T_e)/(T_e^{1/2} \Delta E) \quad (3)$$

with the oscillator strength, f , and gaunt factor $\bar{g}$ taken to be equal to one for generality; and ΔE and T_e expressed in eV. The radiative transition probability, A , is determined by the oscillator strength and is proportional to ΔE^2 . The electron cooling rate per electron per ion, K_e , due to electron excitation of N_g may then be written

$$K_e = \alpha e^{-X}/(1 + \delta/X^3) \text{ ergs cm}^3 \text{sec}^{-1}, \quad (4)$$

where $X = \Delta E/T_e$, $\delta = 3.7 \times 10^{-13} (N_e/T_e^{7/2})$ with N_e expressed in cm^{-3} , and $\alpha = 2.6 \times 10^{-17}/T_e^{1/2}$. K_e is a maximum for real positive values of X (denoted by X_{opt}) satisfying the equation:

$$X^4 + \delta X - 3\delta = 0. \quad (5)$$

The solution of Eq. (5) is illustrated in Fig. 1 which shows X_{opt} versus T_e for values of N_e ranging from 10^{14} cm^{-3} to 10^{21} cm^{-3} . For conditions with low N_e and high T_e , X_{opt} is small as the collisional excitation rate increases with decreasing energy level separation, X . Since the electron density is low, collisional de-excitation does not compete with radiative decay until X is very small. For high N_e and low T_e collisional de-excitation, and hence

electron heating, is more significant for low values of ΔE , and thus the value of X_{opt} increases. The electron cooling rate, K_e , for the case $X = X_{\text{opt}}$ decreases with increasing density. The dependence of K_e on T_e and N_e has been examined in more detail for the case of oxygen in Ref. 9. Figure 2 shows the electron cooling rate, K_e , plotted versus X . Values of X more than a factor of two greater or less than X_{opt} result in a much reduced cooling rate.

To apply this to target design in a recombination pumped, radiatively cooled X-ray laser experiment, one would first identify the range of plasma conditions (N_e , T_e) where it is most critical to have the maximum cooling rate and then from Figs. 1-2 find the optimal energy level separation for these conditions. Candidate ions that are likely to be abundant in the plasma would then be evaluated by matching their energy level structure to the optimum, X_{opt} . Of course, this model can be extended for maximum cooling over a range of temperatures by considering ions with several transitions mapping the range of X_{opt} . Ions with a large number of optically active electrons (f sum rule) may have many transitions in the optimal energy range. If it is desired to reach the shortest possible wavelengths by using the highest ionization stage attainable with the available laser energy, this approach may also be used to pick ions with the minimum cooling rate for the plasma conditions in the ionization phase of the plasma. For specific cases where better theoretical or experimental values for the excitation rate are known, a numerical solution equivalent to maximizing Eq. (4) may be performed. A comparison of this two-level model to a more detailed (~ 100 level) model⁹ of a transient oxygen plasma shows that a strong mismatch between transitions available in the ionization stages abundant in the plasma and the value of X_{opt} results in a much reduced cooling rate.

In conclusion, we have described a simple model which may be used to evaluate ions which are candidates for radiation cooling in recombination pumped X-ray laser schemes.

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FIGURE CAPTIONS

1. Optimum energy level separation $X_{\text{opt}} = (\Delta E/T_e)_{\text{opt}}$ versus T_e for electron densities of $10^{14} - 10^{21} \text{ cm}^{-3}$.
2. Electron cooling rate, K_e , versus energy level separation, $X = \Delta E/T_e$, for $N_e = 10^{19}$, $T_e = 20, 50, 200 \text{ eV}$.

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Fig. 1

Fig. 2

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