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MEASUREMENTS OF POPULATION INVERSION AND GAIN IN CARBON FIBER PLASMAS; THEORETICAL CALCULATIONS OF RADIATIVE COOLING

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Abstract - We have observed an axial enhancement of the CVI 182 Å (3-2) transition which was correlated with the appearance of a population inversion between levels 3 and 2 in an experiment in which a 0.5kJ CO2 laser was focused onto the end of an axially oriented thick (35-350μ) carbon fiber. A maximum gain of k % 6 cm⁻¹ was measured for a carbon fiber coated with a thin layer of aluminum (for additional radiation cooling). We also present theoretical calculations of radiative cooling rates of oxygen appropriate for a high density transient plasma together with a more general model useful for picking the optimum coolant ion.

INTRODUCTION

Since the announcement by Livermore and Princeton Groups at the APS Meeting in Boston (November 1984) of high gain in Se XXV at 206-209 Å and in CVI at 182 Å, respectively, significant progress in the development of soft X-ray lasers is very apparent in this Proceedings and a review of recent progress at Princeton is given in Ref. 1. This paper is devoted to an experimental study of population inversions and gain in carbon fiber plasmas² and also a theoretical study of radiation cooling.³,⁴

Measurement of Population Inversions and Gain in Carbon Fiber Plasmas

In our approach to soft X-ray laser development based on radiation cooling of a plasma confined in a magnetic field, investigation of different targets and the resultant plasma geometries indicated that end-on illumination of a carbon fiber could produce a long thin plasma suitable for high gain and an experiment was set up to measure the gain produced by fast recombination on

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the CVI 182 Å n = 3 \rightarrow m = 2 transition in such a plasma. Significant differences in this work to the approach of G. Pert and M. Key et al. are that (i) the fiber is illuminated end-on (ii) we use a commercially available 1kJ TEA CO₂ laser with a 70 nsec pulse duration and (iii) the fiber is relatively thick (35-350μ) and conduction to the cold fiber core is expected to be more important than adiabatic expansion in cooling the plasma to produce fast recombination.

A description of the experimental set up and calibration procedures is given in Ref. 2. In the experiment, gain was measured by two independent methods: (a) from the ratio of axial to transverse CVI 182 Å emission and (b) from the absolute level of the population difference between levels n = 3 and 2. In the first method the ratio of axial to transverse 182 Å intensity was normalized by the relative sensitivity calibration of the axial and transverse spectrometers. The measured enhancement, E, represents the ratio of stimulated plus spontaneous axial emission to spontaneous emission in the transverse direction. In the absence of gain, E should be unity.

The time history of the CVI 182 Å (3 \rightarrow 2 transition) line emission is shown in Fig. 1 for a \ell = 4.7 mm long, 35μ diameter carbon fiber without the magnetic field. This fiber was coated with 8000 Å of aluminum and generated the highest enhancement of E\%6. The enhancement is related to the gain-length product, k\ell by: E = [exp (k\ell)-1]/k\ell yielding, for this case, k\ell = 3 corresponding to k \%6 cm⁻¹. At the peak of the CVI 33 Å emission (2 \rightarrow 1 transition) the population inversion ratio N₃/N₂ was measured to be 4:3:1. Here N is the population and g the statistical weight. While direct measurements of the CVI geometry in the fiber plasma were not available, a spatial scan of a similar plasma generated from a thin (300μ) carbon blade at B = 0kG, showed the width of the CVI 182 Å emission to be less than 200μ. If, on this basis, the fiber plasma diameter is taken to be 150μ the absolute intensity calibration yields a CVI n = 3 population of 2 \times 10¹⁵ cm⁻³. For this population with a 182 Å Doppler broadened line at 10 eV, the calculated gain is k \%8.2 cm⁻¹ and is consistent with the gain measured from the 182 Å intensity ratio. The aluminum coating was added in order to increase radiation cooling. The brightness temperature of the axial emission calculated from the measured intensity of 4.2 \times 10⁴ watts sr⁻¹, (area 1.8 \times 10⁻⁴ cm²) is 2.2 keV, much higher than the temperature of the recombining plasma. Figure 1(e) shows the complete results from 16 fibers, 8 with a 90 kG magnetic field present. The B = 90 kG data shows no population inversion and no significant axial enhancement, although framing camera images in the visible wavelength range shows that for B = 90 kG the plasma was well contained and elongated, while for B = 0 the plasma extended over a larger volume. The B = 0 kG data, however, shows both population inversions and enhancements. The correlation of observed population inversions with enhancement is strong evidence for stimulated emission.

Rapid cooling after the laser pulse is required in order to generate fast recombination and high gain. For our case of relatively large fiber diameter incomplete ionization of the fiber core provides a low temperature heat sink which can cool the surrounding plasma much more rapidly than adiabatic expansion. A simple calculation has shown that for relatively large fiber diameters, conduction cooling is at least an order of magnitude faster than expansion cooling and is expected to reduce the plasma temperature long before expansion reduces the plasma density appreciably. For B = 90 kG, and if little magnetic flux is excluded from the plasma, the classical electron thermal conductivity decreases by a large factor which can remove conduction as a cooling channel. The absence of inversion and enhancement for B = 90 kG in Fig. 1(e) might also be explained by increased electron collisional coupling between CVI levels n = 2 and n = 3 at the higher densities maintained by the field.

In summary, correlated population inversions and gains have been demonstrated for carbon fiber plasmas with the largest gain being \%6 cm⁻¹. Thermal conduction to the relatively cold fiber core remaining after the laser pulse and radiation losses are proposed as the dominant cooling mechanisms.
Fig. 1 (a) Carbon fiber, (b) CO$_2$ laser pulse, and (c), (d) time-resolved CVI signals from the shot with the highest gain ($\approx 6$ cm$^{-1}$) and 

(e) enhancement ($E$) vs population inversion for 16 fiber shots. Open circles: $B=0$ kG, no Al coating; solid circles: $B=90$ kG, no Al coating; open/solid triangles: fibers with 8000 Å aluminum coating ($B=0$ and $B=90$ kG, respectively).
Radiation Cooling in Steady State and Transient Plasmas at Densities Beyond the Coronal Limit

Radiative power losses and associated electron cooling rates from plasmas are important in many applications and are central to recent work on the development of a soft X-ray laser based on fast radiative cooling of a confined recombining plasma. Calculations of radiative power in the coronal regime are available and have been widely applied to low density plasmas. High electron densities and lower electron temperatures the coronal approximation is no longer valid and the ionization balance (fraction of ions in each charge state) and radiative cooling coefficients (radiated power per ion per electron) become density dependent and differ from the coronal values. We present here some results from a calculation of the radiative cooling properties of oxygen in equilibrium and transiently ionizing and recombining plasmas for electron densities up to \( N_e = 10^{20} \text{cm}^{-3} \). Oxygen was chosen as it is used in the soft X-ray laser development experiment as a medium in which to generate a population inversion, as well as to provide additional radiation cooling for carbon plasmas. In addition, oxygen is present in most laboratory plasmas as an impurity and its radiative power loss properties are of general importance. A more extensive account of this work is presented in Ref. 3 and 4.

Power loss from steady-state plasmas is normally presented in terms of the quantity \( L_x \), which is the radiated power per electron per ion. The total radiated power per \( \text{cm}^3 \) due to a density \( N_T \) of oxygen atoms at a given \( T_e \) and \( N_e \) in steady-state is: \( P_{\text{tot}} = N_T N_e L_x (N_e, T_e) \). Figure 2 shows the steady-state radiative power loss coefficient \( L_x \) at \( N_e = 10^{10}, 10^{16}, 10^{17}, \) and \( 10^{18} \text{cm}^{-3} \). The coronal results of Post et al. are also shown for comparison. The overall shape of the curve, with a peak due to L-shell radiation at low temperatures and a second peak due to K-shell radiation at high temperatures, is preserved at high density. In fact, the K-shell is little changed as the coronal approximation at high temperatures is still relatively good for He-like and H-like oxygen. Below 100 eV, however, collisional deexcitation begins to compete with radiative decay and reduces the power loss coefficient from its coronal value. The onset of collisional deexcitation also results in changes in the composition of the total line radiated power as the electron density is increased. At \( N_e = 10^{10} \text{cm}^{-3} \), 95% of the radiation near \( T_e = 20 \text{ eV} \) arises due to an \( \Delta n = 0 \) transitions. At \( N_e = 10^{18} \text{cm}^{-3} \), however, \( \Delta n = 0 \) contributions represent only 20% of the line radiated power, since these transitions have been quenched by collisional deexcitations.

In steady-state plasmas where the total radiated power is dominated by line emission, the dominant effect of radiation loss is to cool the electrons. In a transient plasma, however, the radiated power reflects potential energy changes due to ionization and recombination as well as electron energy losses occurring through collisional excitation. (During strong three-body recombination, potential energy changes may also result in electron heating.) The instantaneous radiated power depends on the current electron temperature and ionization balance; these in turn depend on the previous evolution of the electron temperature. For this reason, most calculations of radiation from transient plasmas to date have been for a specific electron temperature evolution, with limited applicability to ionizing and recombining plasmas in general.

We have constructed radiated power and electron cooling coefficients that avoid this problem as they do not depend on a specific temporal profile of the electron temperature. Figure 3 illustrates the results for \( ^0\text{S}^+ \) and \( N_e = 10^{18} \text{cm}^{-3} \). Here \( K \) represents the electron cooling rate per \( ^0\text{S}^+ \) ground state per electron and we plot separately the contribution due to excitation, \( K_5' \), and due to recombination, \( K_5'' \). (The recombination term \( K_5'' \) is negative as it represents electron heating). The radiated power coefficients \( P_5' \) and \( P_5'' \) represent the radiated power per \( ^0\text{S}^+ \) ground state per electron due to excitation and recombination respectively. Coefficients for \( ^0\text{S}^+ \) to \( ^0\text{F}^+ \) for a wide range of electron densities together with specific applications are given in Ref. 3.
Fig. 2 Steady-state radiative power loss coefficient for oxygen as a function of electron temperature at several electron densities. The results at $N_e = 10^{10}\text{cm}^{-3}$ are in good agreement with the average-ion coronal model of Post et al.\textsuperscript{8}.

Fig. 3 Electron cooling ($K', K''$) and radiative power ($P', P''$) coefficients per ground state $O^{5+}$ at an electron density of $N_e = 10^{18}\text{cm}^{-3}$. The $K'$ and $P'$ terms are due to excitation and the $K''$ and $P''$ terms due to recombination.
These coefficients have the practical significance that it is possible to obtain the instantaneous radiated power and net electron cooling for an ionizing or recombining plasma from the electron temperature, density, and ground state populations alone. This is a considerable simplification from a time-dependent calculation of the radiated power for a particular electron temperature evolution, and as such these coefficients are suitable for use in hydrodynamic codes to model atomic physics effects on the evolution of the electron temperature.

Finally, 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 the line radiation? We consider a two-level model consisting of a lower level, $g$, and excited level, $i$, which addresses this problem. 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. When the level separation is lower than optimum the excited states decay mostly by collisional deexcitation with little cooling due to radiation. On the other hand if the energy level separation is too large the electron excitation rate is low and again radiation losses are reduced. This is illustrated in Fig. 4 and the results, presented more fully in Ref. 4, may be used to evaluate ions which are candidates for radiation cooling in recombination pumped X-ray laser schemes.

Fig. 4 Electron cooling rate $K_e$ in a two level model versus energy level separation $X = E/T_e$ for $N_e = 10^{19} \text{ cm}^{-3}$, $T_e = 20, 50, 100 \text{ eV}$. 
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