Theoretical study of electron-beam-heated carbon plasma C+++ emission

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The response of an electron beam heated carbon plasma is studied with particular attention given to CIV(C+++) line emission at 2530 Å which has shown promise in plasma lasing schemes. A theoretical model which follows the plasma's hydrodynamics, ionization dynamics, and beam-plasma interactions is used to identify two distinct plasma responses which depend upon the heating rate. The response's difference is caused by variation of radiated power with plasma temperature and density. The model's predictions qualitatively agree with experimental observations at the University of Michigan.

Potential advantages of plasma use as a lasing medium include higher power levels and greater wavelength ranges. The basic concept, first proposed by Gudzenko,[1] is to heat and then rapidly cool a plasma creating an inversion by inducing a bottleneck between the recombination reaction populating a given energy level and the subsequent decay processes. Much effort has been devoted to plasmas heated by lasers[2] and pinch devices.[3] Here we are concerned with electron beam heated carbon plasmas and will focus on the CIV(C+++) $5g$-$4f$ transition occurring at 2530 Å. These studies were initiated to provide theoretical support for experiments at the University of Michigan using the Michigan Electron Long-Pulse Beam Accelerator (MELBA).[4,5]

The theoretical model discussed in the next section was used to study plasma response to various electron beam parameters. The 2530-Å emission time evolution reveals two plasma responses dependent upon the beam heating rate. The response is a consequence of the radiative emission barrier which limits the energy available for plasma heating. Implications of these studies are then considered for MELBA produced and heated plasmas.

The 2530-Å line evolution cannot be studied by only considering plasma ionization dynamics (atomic physics). Heating and cooling rates which depend upon the plasma macroscopic evolution and electron beam-plasma interactions are important. The complete theoretical model consists of three coupled modules describing the plasma hydrodynamics, ionization dynamics, and electron beam-plasma interactions. Primary assumptions assume a one-dimensional geometry, no externally applied electromagnetic fields, and an optically thin plasma.

Plasma macroscopic evolution is described using one-fluid, two-temperature hydrodynamics equations. A collisional-radiative equilibrium model (CRE)[6] consisting of 54 rate equations describing the evolution of 104 quantum energy levels is used to model the ionization dynamics. CRE models generally require one rate equation per energy level, but an averaging technique allows use of fewer equations than energy levels.[7] Atomic processes included are collisional excitation and deexcitation, spontaneous emission, collisional ionization, three-body recombination, radiative recombination, and dielectronic recombination. Rate coefficients were obtained from the Naval Research Laboratory with the calculation techniques catalogued by Duston *et al.*[8] and the energy level structure given by Thornhill, Duderstadt, and Duston.[9]

Collisional and collective electron beam-plasma interactions are considered. Collisional energy loss is described using a stopping power based upon a Fokker–Planck collision operator for a partially ionized plasma.[10] Bremsstrahlung was neglected since collisional energy loss dominates in carbon for electron energies below 29 MeV. Collective processes are difficult to model due to their inherent nonlinear nature. A classification developed by Lau,[11] which assumes a field free plasma and neglects beam electron self collisions, was used to identify and calculate the critical wave number, frequency, and growth rates of potential collective processes.

The critical wavelength yields a critical plasma size which is compared to the actual plasma size to determine occurrence. Growth rates give instability saturation times which are generally much shorter than characteristic plasma hydrodynamic time scales, thus the plasma perceives saturation as instantaneous. The amount of energy transferred through collective interactions is difficult to estimate, but studies indicate the maximum is 30% of the beam energy.[12] The model requires that the user specify the desired percentage.

Equation of state definitions and transport laws provide the coupling between modules. Electron and ion number densities are related using an effective charge. Thermal energies and pressures are calculated with the ideal gas law. The ionization dynamics model yields energy level populations necessary to calculate the ionization energy and radiative power loss. Fourier's law, using Braginkii's[13] thermal conductivities, describes thermal conduction, and interspecies energy transfer is modeled using the Spitzer collision frequency.[14]

The plasma response, especially that of the 2530-Å line, to beam parameter variations was investigated. The general electron-beam plasma system consisted of a 2-cm-long plasma with an initial ion number density of $5\times10^{16}\ \mathrm{cm}^{-3}$ and a 0.3 eV temperature. The electron beam was a square pulse of 1 MeV electrons with the beam power density and pulse length varied to maintain a constant time integrated energy

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transfer. Energy transfer through collective processes was set at low values to prevent unrealistic results.

Two distinct plasma responses labeled types A and B were observed for different heating rates. The 2530-Å emission evolution is illustrated in Fig. 1 for each response. It is desired to maximize the plasma temperature, thus producing a large population of CV(C + + + +) ions. The peak occurring during beam heating results from the plasma ionizing to CIV stage. The beam is turned off and the plasma cooling induces recombination reactions hopefully populating the CIV 5*g* level faster than it can decay, thus producing a population inversion. Plasma cooling and the subsequent recombination reactions hopefully produce an emission peak associated with a population inversion.

Type A behavior occurs for slow heating rates. The type A plasma converts most of the deposited energy into radiation, thus experiencing little heating. This is not undesirable if the radiation is the type desired. Figure 1 shows an ionization peak late in the beam pulse and a recombination peak shortly after the pulse ends. This behavior is acceptable but the intensity is relatively low. The plasma heats nonuniformly with only the plasma edges significantly heating and emitting 2530-Å radiation.

Type B responses occur for fast heating rates. Type B plasmas efficiently convert deposited energy into internal energy resulting in temperatures where CV is the dominant ion species. 2530-Å emission shows a sharp ionization peak and a recombination continuum rather than a peak. The type B plasma experiences fairly uniform heating.

The difference between the two responses is elucidated by considering the radiative power variation with plasma density and temperature shown in Fig. 2. The plasma can only radiate away a certain amount of energy. Any energy supplied in excess of this limit is converted into other forms such as internal energy. There are two important points to note. First, the radiative power peaks at approximately 8 eV forming a barrier which the plasma must "burn through" to efficiently convert deposited energy into forms other than radiative emission. The second is that the barrier height depends upon the ion number density. Thus, for a given energy source, it is easier to burn through the barrier at lower number densities.

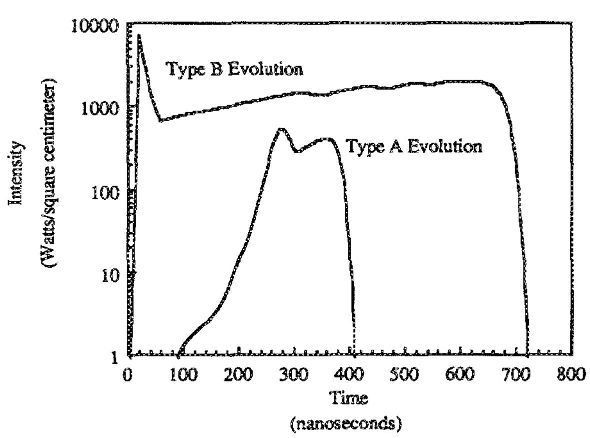

FIG. 1. Type A and type B CIV 2530-Å line emission time evolution for a 2-cm-long plasma of ion number density 5×10^{16} cm^{-3}. The type A response was driven by a 1.0 MeV, 10^6 W/cm^2 electron beam transferring 3% of the beam energy for 300 ns. The type B response was driven by a 1.0 MeV, 5×10^6 W/cm^2 electron beam transferring 3% of the beam energy for 60 ns.

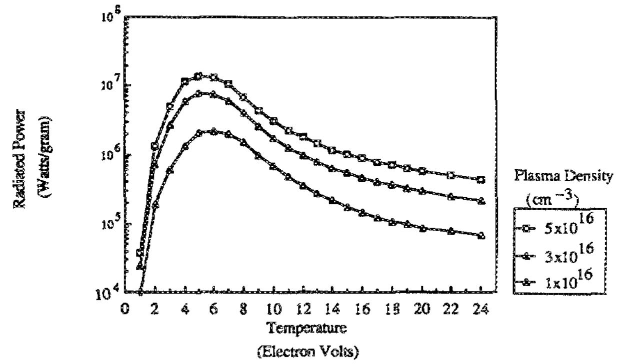

FIG. 2. Carbon radiative emission as a function of electron temperature and ion number density calculated using the collisional-radiative equilibrium model.

The type A response occurs for "slow" heating rates where the deposited energy at any one time is only slightly greater than the radiative emission barrier height resulting in slow plasma heating. Expansion produces lower densities at the plasma edges resulting in lower barrier heights and faster heating. Thus the plasma edges reach higher temperatures than the center.

The type B response occurs during "fast" heating rates where the deposited energy is much larger than the radiative emission barrier height resulting in fast barrier burn-through. Plasma heating is uniform since little expansion occurs during the short beam pulse and the entire plasma burns through the barrier at approximately the same rate.

The heating rates induce different plasma responses, with hotter plasmas arising from faster heating rates. The differentiation between "fast" or "slow" heating rates is determined by how quickly the energy source allows plasma burn through of the radiative emission barrier. Cooling rate effects were not investigated but faster cooling should result in sharper recombination peaks and shortening of the continuum produced by type B plasmas.

These studies were initiated to provide theoretical support for MELBA experiments which recently have examined CIV 2530-Å emission time behavior. Experimental observations indicate that the 2530-Å emission coincides electron beam presence, disappearing shortly after the beam turns off.[15] The line's evolution is not continuously observed, but is deduced from time integrated spectra taken at various times during the experimental runs which yield a general picture of the exact behavior. Bulk plasma temperature estimates are under 10 eV.[4,5]

The expected low plasma temperature regime coupled with the 2530-Å line disappearance at pulse ending indicate that MELBA may be inducing a type A plasma response. Typical MELBA runs were simulated and 2530-Å emission evolution given in Fig. 3 for a plasma density of 5×10^{17} cm^{-3} and 1% instability. Simulation of MELBA is a complex undertaking with details given elsewhere.[16]

Simulations confirm that MELBA may indeed induce a predominantly type A response. The simulations reveal that

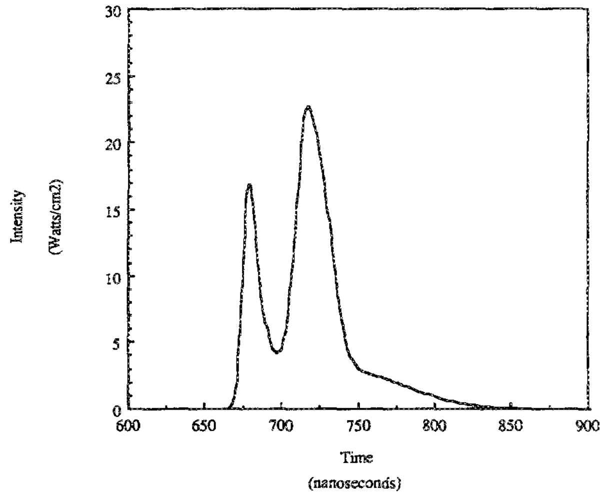

FIG. 3. Theoretical CIV 2530-Å emission for MELBA electron beam-plasma system. Simulation plasma had an initial ion number density of 5×10^{17} cm^{-3} and transferred 1% of the beam energy. Beam pulse ends at 717 ns.

collective processes are responsible for heating the plasma. The plasma temperature distribution is highly nonuniform since the edge quickly expands to lower densities allowing radiative emission barrier burn through while the bulk plasma remains at temperatures below 10 eV. The first peak in Fig. 3 is an ionization peak due to plasma edge heating. The second is not actually a separate peak, but an increase in emission from the bulk plasma interrupted by the end of the beam pulse. The 2530-Å line emission declines by a factor of 5 within 30 ns of the pulse end.

Theoretical studies examining plasma response to electron beam heating rates reveal two characteristic responses. The difference was traced to how quickly the plasma burns through a radiative emission barrier. Type A plasmas occur for slow heating rates which cause slow barrier burn through and little heating. The subsequent 2530-Å emission is of low intensity. Type B plasmas quickly burn through the radiative emission barrier to reach temperatures where significant 2530-Å emission is observed. The model results qualitatively agree with MELBA experimental observations which indicate a type A response.

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Raman scattering study of the high-pressure oxidation of InP

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Air-grown oxide films formed on InP at temperatures below 500 °C are known to contain elemental phosphorus. Recent literature reports indicated that oxidation under high-pressure conditions converted the elemental phosphorus into P_2O_5. We have reexamined this finding for oxygen pressures up to 300 atm using Raman scattering. Red phosphorus is detected in both low- (1 atm)and high- (300 atm) pressure oxidized films independent of the substrate doping type.

It is known that air oxidized films grown around 500 °C on InP contain elemental red phosphorus.[1,2] This phase represents a potential source of traps in the oxide, and it has been argued that if elemental red phosphorus could be eliminated from thermally grown native oxides, then a stable metal-insulator-semiconductor field-effect transistor (MISFET) technology might result. Recently, high-pressure thermal oxidation was examined and the film phases analyzed by x-ray photoemission spectroscopy.[3] These results suggested that elemental phosphorus inclusions were elimin-

