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TEMPORAL MEASUREMENTS OF THE ELECTRON DENSITY
IN HIGH-PRESSURE ELECTRON-BEAM EXCITED XENON PLASMAS*

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ABSTRACT

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The temporal evolution of electron density in high-pressure (50-400 psia) rare gases has been measured. The measurements were carried out in a relativistic e-beam produced plasma by monitoring the absorption of a CO₂ laser passing through the medium. Comparison of experimental results with a theoretical model yields a room temperature rate coefficient of $1.5 \times 10^{-10} \text{ cm}^3/\text{sec}$ for the Penning ionization of excimers in xenon.

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Recently, prodigious advancements have been made in the development of rare gas excimer lasers excited by relativistic electron beams¹. Accordingly, the necessity of understanding the basic mechanisms operative in the kinetic scheme of these systems has become quite apparent. Since many kinetic processes depend directly upon the electron density, it is of great importance to measure both its magnitude and temporal evolution. As will be shown below, such a measurement permits the determination of certain reaction rates, notably those which contribute to the production of electrons in the plasma afterglow.

The electron density measurements were carried out by observing the free-free absorption due to inverse Bremsstrahlung of a CO₂ laser beam passing through the active plasma region². Classically, the expression for the free-free absorption coefficient is given by³

$$\alpha = \frac{4\pi}{3C} \left(\frac{\omega_p}{\omega} \right)^2 \int_0^\infty \frac{v_{in}(v)}{1 + \left(\frac{v_m(v)}{\omega} \right)^2} v^3 \frac{\partial f(v)}{\partial v} dv \quad (1)$$

where ω_p is the plasma frequency, ω is the frequency of the probing laser, $v_m(v)$ is the collision frequency for momentum

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transfer between electrons and neutral atoms, and $f(v)$ is the electron velocity distribution function, here normalized to unity. For the purposes of this investigation, it was assumed that the electrons had a Maxwellian velocity distribution at a temperature T_e ⁴. Measurements of the momentum transfer cross section as a function of electron velocity⁵ were employed to obtain v_m . The integral in eq.(1) was evaluated numerically, and the absorption coefficient tabulated as a function of gas density and electron temperature. For the case of xenon, it was found that the $(v_m/\omega)^2$ term in the denominator of the integrand represents a significant correction at pressures exceeding ~100 psia; thus a simple linear dependence on gas density could not be assumed.

Absorption resulting from electron-ion collisions may be neglected in the range of electron densities, pressures, and electron temperatures encountered here. Simple calculations⁶ indicate that this affect is less than 0.1% of the total absorption.

For electron energies comparable to $\hbar\omega$, quantum corrections to eq. 1 must be considered. In the regime where $v_m/\omega \ll 1$, the quantum expression for the absorption coefficient given by Holstein⁷ can be employed.

For the CO_2 laser, where $h\nu=0.12$ eV., it was found that the quantum calculation presents only a negligible correction above $T_e=0.3$ eV. Kinetic modeling of these systems indicates that the electron temperature lies between 0.5 and 1.5 eV; as a consequence, the classical expression was employed in interpreting the results. For this temperature range, the absorption coefficient is a fairly strong function of the electron temperature. Therefore, the determination of electron density relies upon a knowledge of this parameter as well. For this reason, interpretation of experimental results was carried out by comparison with a theoretical model⁸.

The experimental cell, equipped with NaCl windows, was constructed from stainless steel, and standard high-vacuum techniques were employed in the apparatus. Research grade gases were used in all cases. The electron beam, generated by a Febetron 706, was admitted into the cell through a 2 mil. titanium window supported by a "Hibachi" structure. The beam from a single transverse mode, 10W. CW CO_2 laser was focused into the cell using a 3m. radius of curvature mirror situated so as to minimize spherical aberrations. The beam center was positioned at a distance of 0.15 cm. from the foil, and apertures were placed on either side of the cell to assure proper alignment.

Detection of the CO_2 laser intensity was carried out using a liquid He cooled Cu-doped Ge detector (rise time ≈ 1 ns.) and the signal was observed on a Tektronix 485 oscilloscope. The total rise time of the system was estimated to be less than 2 ns. The beam was chopped to minimize detector heating, and all detection equipment was placed in a doubly-shielded enclosure to reduce the effects of electrical interference.

Measurements of current density and total beam energy were carried out using a Faraday cup and a calorimeter. These measurements, in conjunction with energy loss tables⁹ were used to obtain an approximate energy deposition into the gas. The path length for the absorption was determined from densitometer tracings of bleachable cellophane¹⁰ placed in the path of the electron beam. It was assumed that the plasma was essentially uniform across the excited region, and no attempt was made to consider local density gradients. The measurements thus derived represent an average electron density over the plasma volume probed by the CO_2 laser beam (spot diameter 2mm.)

To determine if the observed absorption was due entirely to inverse Bremsstrahlung processes, or alternatively due in part to bound-free or bound-bound absorption¹¹, the wavelength

of the probing laser was changed from the P(20) line of the $00^0_1-10^0_0$ band to the P(30) line of the $00^0_1-02^0_0$ band by the insertion of a grating in the laser cavity. At 200 psia, xenon, the predicted ratio of the absorption coefficient at these two frequencies is 1.10 as compared to the experimentally observed value of 1.14±.06. We conclude, therefore, that bound-free and bound-bound transitions are unimportant under the experimental conditions encountered.

Measurements of electron density in He, Ar, Kr, and Xe were carried out for different values of the electron-beam energy deposition, and for different pressures. Figure 1 illustrates a typical oscilloscope tracing of the measured absorption in xenon at 300 psia for both a high and a low e-beam excitation level. The small oscillations on top of the signal at late times are instrumental in nature.

It is important to note that the decay at large energy depositions and high pressure consists of a fast component, and a much slower component at later times. The fast component is anticipated in light of the large dissociative recombination rate at these electron densities¹². The slow component may be explained by considering the reaction¹³

which tends to elevate the electron density at later times, before the excimer population has decayed via radiation. To test this hypothesis, 10 torr of oxygen was added to 300 psia of xenon, in order to collisionally quench the excimer population¹⁴. When the measurement was repeated under these conditions, the amplitude of the slow component was reduced below the noise level whereas the fast component was unaffected. Measurements of the UV intensity under similar impurity levels demonstrated that the excimer population does indeed drop below measurable values.

A comparison was made between theoretical and experimental absorption for various values of the rate for the process given in Eq.(2). The results of this comparison are illustrated in figure 2. The theoretical curves were obtained from the kinetic model, using the energy depositions and path lengths discussed above. The best fit to the data at all pressures and energy depositions was obtained with a value of $1.5 \times 10^{-10} \text{ cm}^3/\text{sec}$ for the rate of (2) at room temperature.

One would expect that other reactions such as excimer ionization by collision with electrons would contribute also to the elevation of electron density at

late times. However, due to the high ratio of Xe_2^* density to electron density, and due to the relatively low electron temperature over the whole range of experimental conditions encountered here, the rate of these processes is much smaller than that of the reaction given in Eq.(2). As a consequence, the ionization of excimers by electrons has a negligible effect upon the electron density.

The details of these measurements in various gases, and the subsequent analysis will appear in a forthcoming publication.

FIGURE CAPTIONS

Figure 1. Measurement of CO_2 laser absorption in a 300 psia xenon plasma. Top: Febetron charging voltage 30kV (energy deposition $\sim 0.17\text{J/cm}^3$) Bottom: Febetron charging voltage 20kV (energy deposition $\sim 0.026\text{J/cm}^3$)

Figure 2. Comparison of theoretical (open circles) and experimental (dashed and solid lines) absorption in xenon at 300 psia for a Febetron charging of 30kV.

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ABSORPTION