Population Inversions and the Measurement of Gain in Laser-Produced Plasmas

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We consider plasma conditions leading to a population inversion with respect to the ground state of an ion and problems arising in the measurement of gain in laser-produced plasmas. These considerations indicate that recent reports of superradiant emission in a laser-produced aluminum plasma at 117.41 Å might be subject to reinterpretation.

In this paper, population inversions with respect to the ground state of ions in a high-density plasma are considered and some general problems that can arise in the interpretation of gain measurements in laser-produced plasmas are described. These results suggest that explanations other than the presence of gain might be considered in interpreting measurements made by Jaegle *et al.*[1] in a laser-produced aluminum plasma. Specifically, calculations of plasma conditions for which a population inversion with respect to an ion ground state might occur indicate that such an inversion would almost always favor transitions from the first excited state. From higher excited states of similar energy, gain on the transition with the highest radiative rate (not the 117.41-Å transition suggested in Ref. 1) would dominate. Also, experimental evidence is presented indicating that for the measurement of gain in a laser-produced plasma the two-plasma technique (one plasma playing the role of a source and the other acting as a sample) such as that used in Ref. 1 can be unreliable. Qualitative explanations for the origin of these measurement difficulties are given. Finally, a simple two-component-plasma model is presented that can explain the intensity anomalies observed in an aluminum plasma[2] without speculating on the existence of gain.

Although population inversions with respect to ion ground states in a plasma are generally considered to be unlikely situations, the existence of such inversions was found to be possible theoretically by calculating individual populations of the ground state and first few excited states for hydrogenic ions at various electron temperatures and densities.[3] These calculations, based on a rate-equation approach,[4] indicate that population inversions with respect to the ground state would almost always be largest for the first excited state. These results also apply qualitatively to nonhydrogenic ions. Favorable conditions for attaining such an inversion in a laser-produced plasma are created by generating a plasma of sufficiently high electron density and temperature such that initially some higher ionization stage, $E^{(x+1)+}$, would have a greater population than the next lower stage, E^{x+} (where E denotes the element and x specifies its charge). During the subsequent recombination phase of the plasma evolution, a population inversion of duration $\sim 10^{-10}-10^{-11}$ might then occur in the E^{x+} ionization stage under conditions of unusually rapid cooling.

If these conditions for a population inversion were achieved in a laser-produced aluminum plasma, then the highest gain in the Al^{3+} ion would almost always occur on the $2p^5 3s\,^3P_1 \rightarrow 2p^6\,^1S_0$ transition at 161.69 Å. The minimum electron density required to achieve such a population inversion increases as the electron temperature increases. For example, at an electron temperature of 5 eV the threshold electron density for population inversion in the Al^{3+} ion is $\sim 10^{20}$ cm^{-3}. Population inversions of higher excited states, such as those in the closely spaced $4d$ multiplet considered by Jaegle *et al.*, are also possible. In this case gain would be greatest on those transitions with the largest radiative rates, since the populations of these levels are estimated to collisionally equilibrate in times less than 10^{-10} sec for electron densities greater than 10^{17} cm^{-3}. Experimentally measured collisional mixing rates in other metal ions[5] (when scaled by the ratio of the appropriate Bohr radii) support this estimate. Thus, because of rapid collisional mixing, gain would be greater at 116.46 and 116.92 Å (the transitions to the ground state from the $4d$ multiplet with the highest radiative rates) than at 117.41 Å, and it is unlikely that any particular collisional process which preferentially populates the $^3P_1$ level over the $^1P_1$ and $^3D_1$ levels of the $4d$ multiplet, as suggested by Carillon *et al.*,[6] could have a rate large enough to alter this conclusion. Therefore, since gain is not expected to dominate at 117.41 Å, alternative explanations of the enhancement measured by Jaegle *et al.* might be considered.

In this laboratory, in the course of measurements of excited-state densities in laser-produced metal-vapor plasmas formed in a vacuum and in the presence of a background gas, both the two-plasma technique and a laser-probe technique were used to study the upper and lower levels of the 4416-Å transition in the Cd^+ ion. A cadmium plasma was formed by focusing the 10.6-μm output from a high-pressure, pulsed, CO_2 laser with a cylindrical lens onto a cadmium target inside a vacuum chamber. The 10.6-μm output was focused in such a way that two collinear regions of the cadmium target (each 3 mm long and 0.4 mm wide, separated by 2 mm) were irradiated with intensities of 10^8–10^9 W/cm^2. The resulting collinear plasmas (formed above the target surface) emitted strong radiation during the recombination phase of the plasma in both the neutral and the ionized spectra of cadmium. An optical-detection scheme permitted a small, approximately cylindrical region (parallel to the common axis of the plasmas) to be sampled at any particular height above the target by a high-resolution monochromator. For the two-plasma technique this region was imaged onto a pinhole with $f/25$ optics and subsequently focused onto the slit of the monochromator. For the laser-probe technique, the laser beam passed unfocused through the plasma and continued over a relatively long path (to minimize background light from the plasma) before being focused into the monochromator.

In the two-plasma measurement, the intensity from the two identical plasmas viewed together (I_T) and separately (I_S) gave a measure of the apparent enhancement $[\Delta I = (I_T - 2I_S)/I_S]$ of radiation from the plasma furthest from the detection system in the presence of the plasma nearest the detection system. Enhancements were observed over a wide range of background-gas pressures and in vacuum. As an example of a particularly large enhancement, Fig. 1(a) shows the recorded time dependence of I_S and I_T for the plasma emission at 4416 Å observed 1 mm above the target surface with a background gas of helium at 30 Torr. The resulting enhancement, ΔI, is shown as a dashed curve in Fig. 1(b). Hence, at certain spatial and temporal positions the two-plasma technique indicates (through an apparent enhancement of the 4416 Å emission) the presence of as much as 200% "gain" at 4416 Å in the laser-produced cadmium plasma. A time-integrated measurement of intensity would have shown a smaller enhancement of ~25% which is comparable in

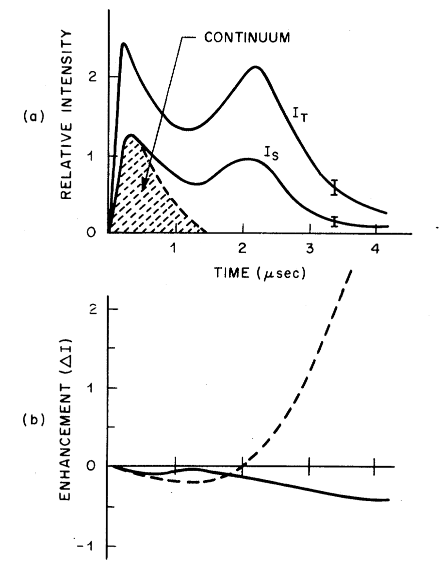

FIG. 1. Experimental comparison of two-plasma and laser-probe techniques at 4416 Å in a laser-produced cadmium plasma. (a) Intensity (average of five pulses) from a single plasma (I_S) and from two plasmas produced together (I_T) as measured by the two-plasma technique. (b) Enhancement measured by two-plasma technique (dashed curve) and absorption from laser-probe measurement (solid curve).

magnitude to the 17% gain deduced from photographic measurements by Jaegle *et al.* at 117.41 Å in a laser-produced aluminum plasma.

A 4416-Å He-Cd laser was subsequently used to probe the laser-produced cadmium plasma in the identical spatial and temporal regions where the presence of gain was indicated by the two-plasma technique. These results, shown as a solid curve in Fig. 1(b), indicate a loss of 40% where the two-plasma technique indicated a 200% gain. When using the laser-probe method it was observed that the plasma produced focusing and deflection of the probe beam. Therefore great care was taken to ensure that all of the laser radiation was properly collected by the detection system. The possibility that the two-plasma technique was monitoring emission or absorption at a frequency shifted from that of the probe laser was also considered. However, a high-resolution measurement of the frequency distribution of the plasma emission at 4416 Å indicated that the frequency of the probe laser was near the center of the broadened line. When these effects were taken into account it was concluded that the laser-probe technique gave a reliable measurement of plasma absorption. Therefore, effects other than stimulated emission can apparently cause the two-plasma technique to give an incorrect indication of gain.

The presence of a second plasma can significantly perturb emission from the first through energy transfer via optical pumping or collisional interaction, while refractive-index gradients within the plasmas can strongly affect the emission reaching the detection system. The energy-transfer effects may be particularly important in interpreting the results of the two-plasma technique for the 117.41-Å transition in a laser-produced aluminum plasma, since measurements by Carillon *et al.* showed that such a plasma is optically thick for 116.46- and 116.92-Å transitions.[6] Radiation emitted by either plasma at these wavelengths would optically pump the other with a net transfer of energy to the weaker 117.41-Å line through strong collisional coupling within the $4d$ multiplet. Also, if the plasmas overlap while still strongly radiating, the interaction could produce changes in plasma conditions resulting in increased emission at 117.41 Å. The presence of index gradients due to large spatial variations in electron density or strong plasma absorption could produce strong focusing and deflection effects in the laser-produced plasmas. For example, the plasma nearest the detection system might act as a lens concentrating radiation from the other plasma onto the detection system. Since focusing and deflection of 4416-Å radiation by a cadmium plasma was observed during the laser-probe measurement it is possible that refractive-index gradients are at least partially responsible for the apparent enhancement measured at 4416 Å.

Prior to their report of measured gain at 117.41 Å, the possibility of stimulated emission at this wavelength had already been suggested by Jaegle *et al.* to explain the occurrence of some "intensity anomalies" appearing in a spectrogram of a laser-produced aluminum plasma.[2] Near the target the transitions from the $4d$ multiplet to the Al^{3+}-ion ground state having large radiative rates (i.e., the 116.46- and 116.92-Å lines) appeared as broad absorption features on a continuum background, whereas the 117.41-Å line with the smaller radiative rate appeared as a narrow emission line above the background. Such anomalies were recently attributed by Valero[7] to the presence of an absorbing region in the plasma.

A two-component model (not necessarily intended to describe specific details of a laser-produced plasma) when fitted with specific ab-

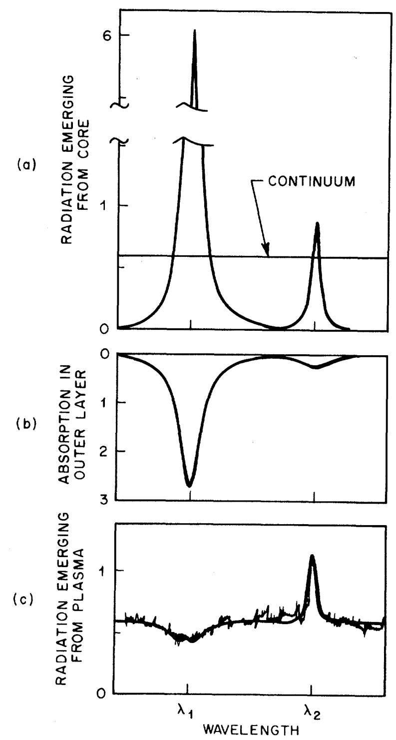

FIG. 2. Plasma emission resulting from a two-component plasma model compared to the 116.92- and 117.41-Å emission from a laser-produced Al plasma of Jaegle *et al.* ["experimental" curve of Fig. 2(c)].

sorption and emission values can reproduce the "intensity anomalies" reported by Jaegle *et al.* without speculating on the existence of gain. As a simplification, the model considers emission in the region of two wavelengths (λ_1 and λ_2) corresponding to transitions having a 10-to-1 ratio of radiative rates from two excited levels to the ground state of an ion. One component of the model is the plasma core and the other component is an outer layer which absorbs emission from the core but whose own emission is negligible. The emission emerging from the core is shown in Fig. 2(a). The continuum emission might occur during the heating phase when the plasma is hot and dense while the narrow-line emission might occur at a later time [as suggested by experiments in this laboratory, see Fig. 1(a)] during recombination when the plasma has cooled. The intensities for the line emission have been calculated under the assumption of equal upper-level populations (e.g., by collisional coupling) and core absorptions of 1.0 at λ_1 and 0.1 at λ_2. This assumption results in the stronger transition at λ_1 being broadened and partially self-absorbed as shown in Fig. 2(a). The absorption of the outer layer is given in Fig. 2(b). The radiation emerging from such a plasma (core radiation passing through outer absorbing layer) is shown in Fig. 2(c). The anomalous features of a portion of the spectrogram obtained by Jaegle *et al.* for laser-produced aluminum plasma are also reproduced in Fig. 2(c) and are seen to be in good agreement with the predictions of the model. A slightly more complex plasma model, incorporating different absorptions for the continuum and line radiation to simulate a time-dependent outer-layer absorption [as suggested by the results of the laser-probe measurement shown in Fig. 1(b)], leads to an even better fit to the results of Jaegle *et al.*

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Plasma-Return-Current Heating by Relativistic Electron Beams with $\nu/\gamma \sim 10$*

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We report experimental results of hydrogen-plasma heating using very intense relativistic electron beams with ν/γ up to 10. The beam-plasma interaction process is found to be plasma-return-current heating with strongly anomalous plasma resistivity. Peak plasma energy is 1.5×10^{19} eV/cm^3, corresponding to $T_e = 2.2$ keV at $n_e = 6.7\times10^{15}$ cm^{-3}.

The use of intense relativistic electron beams to heat plasma has been investigated by several workers, primarily in order to apply the large beam energies available at high power to the goal of heating plasma to thermonuclear temperatures. Previous experiments[1,2] have generally utilized beam energies of $\lesssim 2$ kJ, with $\nu/\gamma \lesssim 2$. The measured plasma energy has been $\sim 10^{17}$ eV/cm^3. The interaction causing the heating has been ambiguous in some cases,[1] and identified as electron-electron beam-plasma interaction in others.[2] Theoretical studies indicate that with high-ν/γ beams, return-current heating will be the dominant plasma-heating process.[3]

We report here the results of initial experiments using a very intense beam (500 kA, 40 kJ, $\nu/\gamma = 10$). Plasma heating of 10^{19} eV/cm^3 is measured. We find that plasma energy gain and beam energy loss are due to return-current heating: (1) The measured total energy loss per transported beam electron is found to equal $e\int E_z\,dz$, where E_z is the independently measured, macroscopic, induced axial electric field which retards the beam; (2) the plasma energy determined from diamagnetic signals, W_m, agrees well with plasma energy density due to Ohmic heating by the plasma return current, independently determined from $W_{\rm Ohm} \equiv \int_0^{\tau_b} J_p(z,t)E_z(z,t)\,dt$, where J_p is the axial plasma current and τ_b the beam duration. (The contribution from azimuthal currents and fields is small.) Together these observations show that the beam-plasma interaction process is return-current heating.

The experiment consisted of injecting the intense relativistic electron beam through the transmission anode foil of the beam-generating diode, which was one end of a metallic hydrogen-filled cylindrical chamber of radius $r_w = 7.5$ cm. The neutral hydrogen fill pressure ranged from 30 to 1000 mTorr (atomic densities of 2×10^{15} to 6.7×10^{16} cm^{-3}, respectively). A 16-kG longitudinal magnetic field permeated both the 1.1 m chamber and the vacuum diode. No provision for plasma containment was made. The OWL II