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Ultraviolet Fluorescence by Optical Pumping with Extreme Ultraviolet Line Radiation

J. Trebes and M. Krishnan
Applied Physics Section, Yale University, New Haven, Connecticut 06520

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Extreme ultraviolet Al III line radiation at 56.0433 nm from a laser-produced plasma is used to optically pump a nearly coincident transition at 56.0437 nm in C II produced in a vacuum arc. Time-resolved measurements of the resultant C II ultraviolet fluorescence at 213.8 nm revealed up to a factor-of-8 increase in fluorescence, coincident with the Al laser-produced plasma.

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The use of optical pumping by line radiation to achieve population inversions was first proposed by Vinogradov *et al.*[1] and by Norton and Peacock,[2] in 1975. In this scheme, intense line radiation from one species selectively pumps a nearly coincident transition in another species. The upper level of the pumped transition can then be inverted with respect to lower-lying levels. Several candidate systems have been proposed for lasing at soft-x-ray wavelengths using this approach. These include Ni XXII pumping Ne IX with lasing at 29.3 nm,[3] C VI pumping C V with lasing at 18.7 nm,[2] and Si XIII pumping Al XII with lasing at 4.4 nm.[4] Experimental tests of these schemes are planned or are underway at several major laboratories. The basic approach for these experiments is as follows: A high-power (10^{14}–10^{15} W/cm^2), pulsed laser is focused onto a sophisticated, multicomponent target, producing a plasma containing both the pump and the lasing ion species. Soft-x-ray lasing on ~10-ps time scales is predicted.[5] However, the concept which is central to the above schemes, i.e., optical pumping using overlapping transitions in different ion species, has not been experimentally verified to data. The present work is motivated by the fact that this novel mechanism is readily verified at longer wavelengths with less stringent experimental requirements. For example, the pump power required for inversion scales as λ^{-4}.[6] Therefore, lasing at 200 nm requires 10^4 times lower pump power than lasing at 20 nm. Furthermore, the transition rates of the pertinent levels are correspondingly longer in the 200-nm regime with a consequent relaxation of the required pump rates. Two such longer-wavelength tests of selective optical pumping are proposed here: Mg VI pumping C III with lasing at 62.2 nm or possibly at 48.4 nm, and Al III pumping C II with lasing at 213.8 nm. In addition, Elton[7] has suggested He II pumping Be IV with lasing at 117.2 nm.

This Letter reports the first experimental observation of selective optical pumping using line radiation. In the measurements described herein, line radiation from the optically thick, $3s$-$5p$, 56.0433-nm Al III transition produced in an Al laser-produced plasma pumped the C II $2p$-$5d$, 56.0437-nm transition in a laser-initiated carbon vacuum arc. The resultant enhanced fluorescence of the C II $3p$-$5d$, 213.8-nm lines was measured in coincidence with the Al laser-produced plasma. Enhanced ultraviolet fluorescence has been elegantly demonstrated earlier by Zych *et al.*[8] However, it is emphasized that the two-photon process described in Ref. 8 is distinctly different from the single-photon, direct optical pumping process described here.

The experimental arrangement is shown schematically in Fig. 1. Two Lumonics, 15 J, 150 MW, pulsed, 10.6-μm CO$_2$ lasers were used. Laser I was focused on the 6-mm-diam graphite target, which was biased to −5 kV by a nearly critically damped *RLC* network. The plasma produced by laser I triggered a 6-kA peak current, 36-μs-duration, vacuum arc discharge from the C cathode target to the coaxial C anode. After a selected delay, laser II was focused to a 2-mm-diam focal spot on the Al target, producing an Al plasma. Several delays were tried and enhanced C II fluorescence at 213.8 nm was observed for all but very early and very late phases of the vacuum arc. For the results presented here, a fixed delay of 26 μs after initiation of the arc was used. As shown in Fig. 1, boron nitride electrically isolated the Al target from the C target. The top surface of the Al target was 15 mm above the C target and 8 mm off the discharge axis. The location of the object plane (0.2×1 mm^2) of the vacuum ultraviolet (vuv) monochromator is also shown in Fig. 1. This is the plasma region from which the 213.8-nm, C II line radiation was detected. The observation region 15 mm above the C target was chosen both to avoid continuum background near the C cathode and

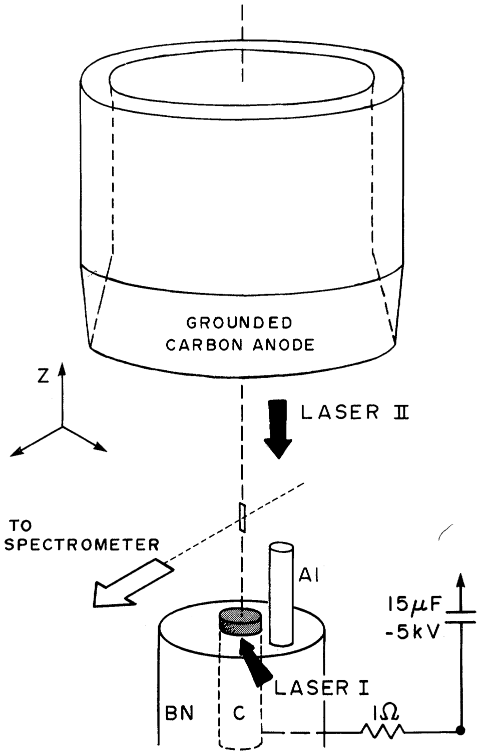

FIG. 1. Schematic of the experimental arrangement.

because a significant C II ground-state population was expected at this location. The Al target was located off axis to minimize spurious continuum at the 213.8-nm wavelength due to the Al plasma. Spectrometers were not available to detect the Al III, 56-nm lines. However, copious ultraviolet and visible line radiation originating from states above and below the $5p$ Al III upper state was observed. This observation is consistent with the assumption that the Al III 56-nm line is intense. To monitor the Al laser-produced plasma, the Al III, $4p$-$5s$, 371.3-nm line was detected by a 0.25-m spectrometer, which viewed the plasma at the Al target surface in a transverse direction.

The details of the optical-pumping scheme are shown in Fig. 2, which shows a partial Grotrian diagram for Al III and C II. The apparent wavelength mismatch between the 56.0433-nm Al III pump line and the 56.0437-nm C II line is 3.6×10^{-4} nm. Such a mismatch can be readily overcome by Doppler broadening. For example, an Al plasma at 5 eV gives a Doppler width of 1.86×10^{-3} nm, which is a factor of 5 larger than the wavelength mismatch.

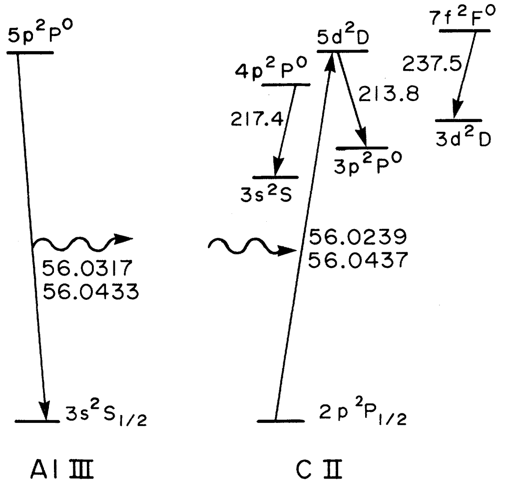

FIG. 2. Partial Grotrian diagrams for Al III and C II (all wavelengths in nanometers).

This particular experimental arrangement was motivated by the requirement, for such optical pumping, of two plasmas with distinctly different plasma parameters. On the one hand, the plasma containing the pump ion species should be dense and hot to maximize the pump line intensity. On the other hand, the plasma containing the pumped species should have densities and temperatures which minimize collisional excitations, while maximizing the ground-state population of the pumped species. If one estimates that the density of Al III near the surface of the Al target is $\sim 10^{17}$ cm^{-3} and $T_i \sim 5$ eV, the optical depth at line center of the 56-nm Al III pump line is ~ 100, for an assumed oscillator strength of 0.01. This in turn implies near blackbody intensity in the pump line. Similarly, assuming that the C II density in the arc is $\sim 10^{14}$ cm^{-3} and $T_i \sim 2$ eV, the optical depth at line center of the absorbing transition in C II is ~ 0.5, again for an oscillator strength of 0.01. Such an optical depth is consistent with volumetric absorption of the Al III pump radiation by the carbon plasma. During the time interval over which Al III line radiation is intense, C II ions will be selectively pumped into the $5d$ upper state. One would simultaneously expect enhanced fluorescence at 213.8 nm.

Experimental evidence for such enhanced fluorescence is shown in Fig. 3. Figure 3(a) shows the temporal evolution of the spontaneous 213.8-nm C II line radiation averaged over 10 shots, in the absence of an Al laser-produced plasma. Figure 3(b) shows the temporal evolution of the vacuum arc current. Also shown in this figure is the 371.3-nm Al III line radiation detected when laser II was fired 26 μs after initiation of the vacuum arc. The effect of the Al laser-produced plasma on the C II line radiation is shown in Fig.

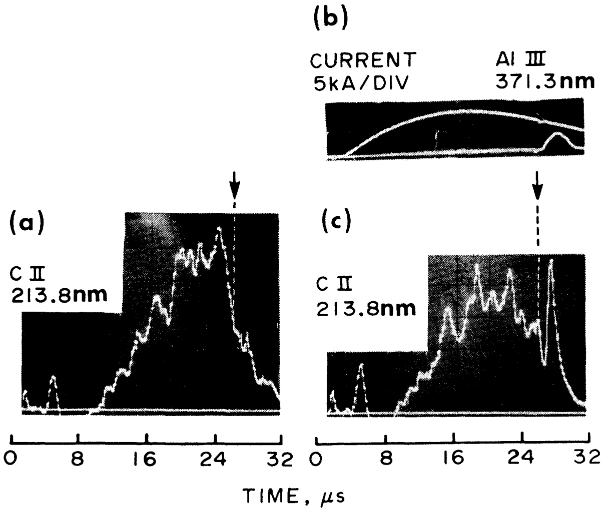

FIG. 3. Optical pumping of C II by Al III: (a) 213.8-nm C II line radiation vs time; (b) discharge current and 371.3-nm Al III line radiation vs time; (c) 213.8-nm C II line radiation vs time, with laser II fired at the instant shown by arrow, to produce an Al pump plasma.

3(c), which shows the 213.8-nm radiation vs time, averaged as before over 10 shots. An arrow and a dashed line on both Figs. 3(a) and 3(c) indicate the instant of firing of laser II. It is observed that the 213.8-nm C II line radiation is considerably enhanced by the presence of the Al laser-produced plasma. Comparison of Figs. 3(a) and 3(c) reveals a fluorescence enhancement of up to a factor of ~3 above the spontaneous C II emission. Single-shot enhancements of up to a factor of ~8 were observed. Such enhancements persisted for approximately 1 μs. These enhancements are not inconsistent with rough estimates of the 5*d* population based on a simple three-level quasistatic model. This model includes photoexcitation, direct collisional excitation to and ionization from the 5*d* level, and spontaneous decay. Under the assumption that the Al III pump line intensity is that of a blackbody at 5 eV, the C II 5*d* population is optically pumped to a factor of 5 above the local-thermodynamic-equilibrium value corresponding to a 2-eV carbon plasma temperature. The observed enhanced fluorescence does not necessarily imply gain at 213.8 nm. Optimization of the pumping process as a prelude to gain measurements is underway.

To confirm that the enhanced emission was not merely spurious continuum at 213.8 nm due to the Al plasma, the continuum background was measured as follows: The delay of laser II was increased to 200 μs, so that the Al plasma was created well after the arc discharge had terminated. This enabled both Al plasma continuum and C line radiation at 213.8 nm (due to any possible deposition of C on the Al target top surface by the arc) to be measured. The background signal so measured was a factor of 9 below the enhanced fluorescence, confirming that the Al plasma significantly pumps the 5*d* level of C II.

To examine whether the enhanced fluorescence could have been due to collisional effects, the vuv monochromator was centered in turn on two C II wavelengths from transitions adjacent to the 3*p*-5*d* transitions. These transitions, 3*s*-4*p* at 217.4 nm and 3*d*-7*f* at 237.5 nm, are shown in Fig. 2. Any collisional pumping should populate the 4*p* and the 7*f* levels as well as the 5*d* levels, since the energy differences (~2 eV) between these levels are small compared with their energies (~22 eV) above the ground state. Under similar experimental conditions, no enhanced fluorescence was observed at these adjacent C II wavelengths. This confirmed that the enhanced fluorescence was not caused by collisional pumping due to the laser plasma.

One further experiment was performed, in which the Al target was replaced by a Mg target of identical geometry. There are no transitions in Mg or its ions which overlap the 2*p*-5*d* C II transitions. The nearest Mg transition is at 55.822 nm in Mg VII. The wavelength mismatch between the Mg VII–C II transitions, 2.22×10^{-1} nm, is a factor of 600 greater than the mismatch between Al III–C II transitions. Therefore, no optical pumping of the 2*p*-5*d* C II transition is expected with a Mg laser-produced plasma. Experiments similar to those with the Al target were performed, and no enhanced fluorescence was observed. This result confirmed the conclusion that the 5*d* upper levels in C II are selectively pumped by Al III line radiation at 56.0433 nm.

One other mechanism, three-body recombination, might be considered as a source of enhanced population in the C II upper levels. Such a mechanism would proceed as follows. Suppose the laser-produced plasma caused changes in the local electron density and temperature so as to enhance three-body recombination of C III ions to C II ions. At these temperatures the recombined C II ions would be populated preferentially in the upper excited states. Collisional-radiative cascading would then populate the 4*p* and 7*f* as well as the 5*d* levels in C II, with fluorescence at many wavelengths coincident with the laser plasma.

The confinement of the observed fluorescence to the $3p$-$5d$ transitions in C II and the absence of fluorescence with the Mg plasma were proof that three-body recombination pumping was not the cause of the observed fluorescence.

In summary, selective optical pumping of an upper state in one ion species using nearly coincident line radiation from another species has been experimentally demonstrated. While the fluorescence observed is in the ultraviolet, the concept verified here is the principal pumping scheme for a new generation of soft-x-ray laser experiments. With the modest pump powers available to us, experiments in the x-ray regime are not feasible. However, extreme ultraviolet fluorescence measurements at 62.2 and 48.4 nm based on the $2s2p^4$-$2s^22p^3$ Mg VI line at 29.135 nm pumping the $2s5p$-$2s^2$ C III transition at 29.133 nm are underway.

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Plasma Edge Turbulence

Akira Hasegawa
Bell Laboratories, Murray Hill, New Jersey 07974

and

Masahiro Wakatani
Plasma Physics Laboratory, Kyoto University, Uji, Kyoto, Japan 611

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Model mode-coupling equations for the resistive drift-wave instability are derived and numerically solved to study the properties of turbulence near a plasma edge. The wave-number spectrum of the turbulence is found to exhibit an inverse cascade to form an isotropic, two-dimensional Kolmogorov spectrum, k^{-3}, in the large-wave-number regime. The turbulence has a broad frequency spectrum with a large saturation level and produces Bohm-type particle diffusion.

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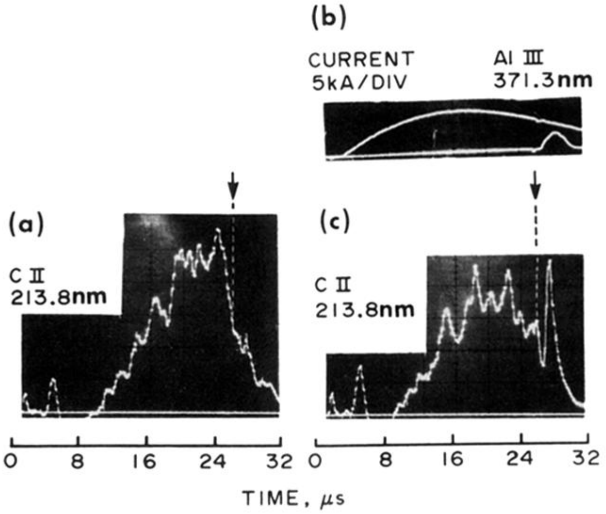
A number of experiments now clearly indicate that a tokamak-type plasma with a strong magnetic field exhibits a large level of density fluctuations which increase near the edge.[1,2] The observed frequency spectra are usually broader than the drift-wave frequency revealing their strongly turbulent nature.[1-3]

Recognizing that the classic weak-turbulence theory fails to explain these results, Fyfe and Montgomery[4] as well as Hasegawa, Kodama, and Maclennan[5] have presented theories of strongly turbulent drift waves based on the model equation derived by Hasegawa and Mima.[6] It was found that the wave-number spectrum rotates from that peaked in the azimuthal direction to that peaked in the radial direction[5] and that the spectrum obeys the two-dimensional (2D) Kolmogorov law.[4,7]

The importance of mode coupling in such strongly turbulent plasmas is now being recognized by many authors. In particular Waltz[8] as well as and Terry and Horton[9] have made extensive nu-



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