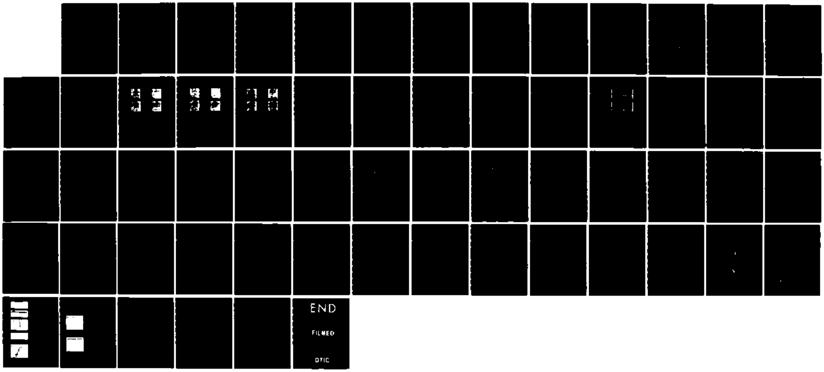
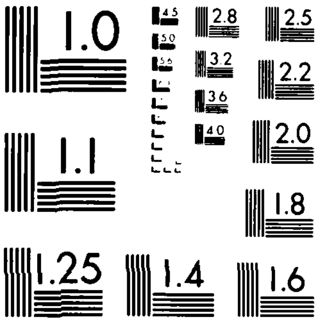
AD-A151 958 POPULATION INVERSION IN LASER-INITIATED VACUUM ARCS(U) 1/1
YALE UNIV NEW HAVEN CONN M KRISHNAN 25 JAN 85
AFOSR-TR-85-0258 AFOSR-81-0077

UNCLASSIFIED F/G 20/5 NL




1.0
4.5
5.0
5.6
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

AD-A151 958

DTIC FILE COPY

UNCLASSIFIED

(2)

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFOSR-TR- 85-0258	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Population Inversions in Laser-Initiated Vacuum Arcs		5. TYPE OF REPORT & PERIOD COVERED Annual Report 2/1/84 - 1/31/85
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Mahadevan Krishnan, Associate Professor of Applied Physics and Mechanical Engineering		8. CONTRACT OR GRANT NUMBER(s) AFOSR- 81-0077
9. PERFORMING ORGANIZATION NAME AND ADDRESS Yale University New Haven, CT 06520		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2301/A8
11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NP Bolling Air Force Base Washington, DC 20332		12. REPORT DATE January 25, 1985
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release;
distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC
ELECTE
APR 0 3 1985
D

18. SUPPLEMENTARY NOTES

E

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Short Wavelength Lasers
X-ray Lasers
Vacuum Arcs
Laser Plasmas

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A detailed study of resonant photo-excitation of CII ions in a vacuum arc discharge by line radiation from laser produced, AlIII ions was completed. Although enhanced fluorescence by up to a factor of eight in CII at 2138 Å was observed, the collisional-radiative kinetics are such as to prevent a population inversion from building up under the conditions

(Continued on next page)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

85 03 13 014

of the experiments. This unfavorable conclusion prompted the identification of a new class of Be-like, photo-excited lasers with potential laser wavelengths from 2177 Å in CIII down to 230 Å in MgIX. Design considerations for such lasers are presented. Initial experiments in CIII pumped by MnVI line radiation have shown fluorescence enhancements in CIII at 2177 Å by up to a factor of 150. Optimization of the pump plasma geometry has increased this enhancement to a factor of 500. Gain estimates are given which suggest that a laser can be constructed at 2177 Å.

Accession For
X

A-1

I. INTRODUCTION

This Annual Scientific Report covers the period February 1, 1984 to January 31, 1985 for AFOSR Grant No. 81-0077. Section II summarizes the research performed during this period. Section III lists the personnel associated with this effort and the publications and presentations which have stemmed from the research.

II. RESEARCH SUMMARY

At the start of this period, Mr. James Trebes entered the final phase of his dissertation research on selective photo-excitation of CII ions by AℓIII radiation. The experiments and the computer-aided analysis which were focused on this excitation scheme are concisely summarized in a paper presented at the 2nd Topical Meeting on Laser Techniques in the Extreme Ultraviolet, Boulder, CO, March 5-7, 1984. This paper, which was published in the AIP Conference Proceedings, is appended to this report as Appendix I. The salient features of this research are reviewed very briefly here. The experiments attempted to characterize the carbon discharge and the aluminum pump plasma in as much detail as possible. Electron density and temperature were measured and/or estimated in both plasmas. A detailed collisional-radiative code was written for the n=3, 4, and 5 levels in CII, using atomic data provided by Dr. W. L. Morgan of Lawrence Livermore Labs. For the given density and temperature in the carbon discharge, it was found that collisional coupling between the n=3, 4, and 5 levels in CII was so strong as to prevent the build-up of a population inversion of the pumped 5d level. Mr. James Trebes completed the writing of his Ph.D dissertation on this topic and left Yale in May 1984 to take up employment at Lawrence Livermore

Labs, where he is active in their x-ray laser program. Mr. Trebes successfully defended his dissertation in September 1984 and was awarded the Ph.D degree in December 1984.

One outgrowth of Trebes' research was the identification of a new class of photo-excited lasers in Be-like ions. This new class of lasers is described in an Applied Physics Letter, "Proposed new class of optically pumped, quasi-cw, ultraviolet and extreme ultraviolet lasers in the Be isoelectronic sequence," Mahadevan Krishnan and James Trebes, Appl. Phys. Lett. 45, 189 (1984). This letter is included as Appendix II.

Detailed design considerations for these lasers were analyzed and presented at the Boulder Meeting in March 1984. These results were also published in the AIP Conference Proceedings as cited below.

> "Design Consideration for Optically Pumped, Quasi-cw, UV and XUV Lasers in the Be Isoelectronic Sequence," Mahadevan Krishnan and James Trebes, in: Laser Techniques in the Extreme Ultraviolet (OSA, Boulder, Colorado, 1984), S.E. Harris and T.B. Lucatorto, Eds. (AIP, New York, 1984), p. 514.

This paper is also included as Appendix III for ready reference.

Finally, in June 1984, Dr. Hayrettin Kilic joined the group as a Postdoctoral Associate Research Scientist. Since June 1984, a graduate student, Mr. Niansheng Qi, the Principal Investigator, and Dr. Kilic have conducted tests of the first of the proposed new lasers, CIII pumped by MnVI. An immediate and exciting result was the observation of fluorescence enhancements in CIII at 2177 Å by up to a factor of 150:1. These results are summarized in a paper entitled, "Observed Enhanced Fluorescence at 2177, 2163, 1923, and 1620 Å in CIII by photo-excitation with MnVI Line Radiation at 310 Å," by Niansheng Qi, Hayrettin Kilic, and Mahadevan

Krishnan, which will be published in the March 1, 1985 issue of Applied Physics Letters. A preprint is included as Appendix IV for convenient reference.

III. PERSONNEL AND PRESENTATIONS/PUBLICATIONS

Personnel:

Mahadevan Krishnan, Principal Investigator
Hayrettin Kilic, Associate Research Scientist
James Trebes, graduate student (left Yale in May 1984), Ph.D awarded December 1984
Niansheng Qi, graduate student

Presentations:

"Optically Pumped Short Wavelength Lasers," Atomic Physics Seminar, Yale University, February 1, 1984.

"UV Fluorescence by Optical Pumping with Line Radiation," Poster Session, 2nd Topical Meeting on Laser Techniques in the Extreme Ultraviolet, Boulder, CO, March 5-7, 1984.

"Proposed New Class of Optically Pumped, Quasi-cw, UV and XUV Lasers in the Be Isoelectronic Sequence," Poster Session, 2nd Topical Meeting on Laser Techniques in the Extreme Ultraviolet, Boulder, CO, March 5-7, 1984.

"A Proposed New Class of Optically Pumped, Be-like Lasers at UV to Soft X-ray Wavelengths," Lawrence Livermore Labs, Livermore, CA, June 20, 1984.

"Proposed New Lasers in the Be-isoelectronic Sequence: Preliminary Results in the UV," Lawrence Berkeley Labs, University of California, Berkeley, CA, June 21, 1984.

"Short Wavelength Lasers: Research and Applications," Summer Research Program Colloquium, Yale University, July 11, 1984.

"Proposed New Lasers in the Be-isoelectronic Sequence: Preliminary Results in the UV," Princeton Plasma Physics Lab, Princeton, NJ, September 11, 1984.

"Short Wavelength Lasers," Physics International Co., San Leandro, CA, October 4, 1984.

Presentations (Cont'd):

"Design Considerations for Optically Pumped, Quasi-cw, UV to Soft X-ray Lasers in Be-like Ions," Poster Session, Annual Meeting of the APS Plasma Physics Division, Boston, MA, October 29-November 4, 1984. (A copy of the abstract is included in Appendix V).

"Observation of Enhanced Fluorescence at UV Wavelengths in CIII by Optical Pumping with MnVI Line Radiation," Poster Session, Annual Meeting of the APS Plasma Physics Division, Boston, MA, October 29-November 4, 1984. (A copy of the abstract is included in Appendix V.)

"Optical Pumping of CIII Ions in a Magnetically Confined C Plasma Using MnVI Line Radiation from an Adjacent Mn Plasma," Poster Session, Annual Meeting of the APS Plasma Physics Division, Boston, MA, October 29-November 4, 1984. (A copy of the abstract is included in Appendix V.)

"Photo-Excited, Extreme Ultraviolet Lasers," Institute for Advanced Studies, Aerospace Technical Center (CTA), Sao Jose dos Campos, Brazil, November 24, 1984.

"Photo-Excited Beryllium-like Lasers from 200-2000 Å. Preliminary Results at Yale in CIII Ions Pumped by MnVI Ions," University of Campinas, Quantum Electronics Division, Campinas, Brazil, December 13, 1984.

"Photo-Excited Lasers from the Ultraviolet to the Extreme Ultraviolet," Colloquium, Mechanical Engineering Department, University of Rochester, Rochester, NY, January 17, 1985.

Publications:

M. Krishnan and J. Trebes, "Design Considerations for Optically Pumped, Quasi-cw, UV and XUV Lasers in the Be Isoelectronic Sequence," in: Laser Techniques in the Extreme Ultraviolet (OSA, Boulder, Colorado, 1984), S.E. Harris and T.B. Lucatorto, eds. (AIP, New York, 1984), p. 514.

J. Trebes and M. Krishnan, "UV Fluorescence by Optical Pumping with Line Radiation," in: Laser Techniques in the Extreme Ultraviolet (OSA, Boulder, Colorado, 1984), S.E. Harris and T.B. Lucatorto, eds. (AIP, New York, 1984), p. 387.

M. Krishnan and J. Trebes, "Proposed New Class of Optically Pumped, Quasi-cw, Ultraviolet and Extreme Ultraviolet Lasers in the Be Isoelectronic Sequence," Appl. Phys. Lett. 45, 189 (1984).

N. Qi, H. Kilic, and M. Krishnan, "Observed Enhanced Fluorescence at 2177, 2163, 1923, and 1620 Å in CIII by Photo-Excitation with MnVI Line Radiation at 310 Å," to be published in Appl. Phys. Lett. (March 1, 1985).

Publications (Cont'd):

M. Krishnan and J. Trebes, "Parametric Analysis of Optically Pumped, Quasi-cw, Ultraviolet and Extreme Ultraviolet Lasers in the Be Isoelectronic Sequence," in preparation.

UV FLUORESCENCE BY OPTICAL PUMPING WITH LINE RADIATION

James Trebes and Mahadevan Krishnan
Yale University, New Haven, Connecticut 06520

ABSTRACT

Optical pumping of CII ions in a vacuum arc discharge using AℓIII ions in a laser produced plasma is described. The CII, 2p-5d, 560.437 Å transition was selectively pumped by line radiation from the AℓIII, 3p-5s transition at 560.433 Å. The wavelength mismatch is less than the Doppler width of the AℓIII line. Four transitions in CII, from the 5d, 5f, 4s, and $2p^2$ levels were studied simultaneously to examine the collisional-radiative redistribution of the pumped, 5d population. Electron density and temperature were measured in the C plasma. The Aℓ plasma was characterized by measurements and numerical modeling in order to estimate the intensity of the AℓIII pump line. A collisional-radiative model of the CII level populations was constructed with the measured density and temperature as inputs. Comparison of this model with the measurements allows discussion of the feasibility of building a UV laser with such a pumping scheme.

INTRODUCTION

Among the many approaches to the production of short wavelength population inversions is that of optical pumping with line radiation. In this approach, intense line radiation in one ion species is used to pump a nearly coincident transition from the ground state to a highly excited state in another ion species. The pumped, upper level may then be inverted with respect to lower lying levels. A survey of prior research in this field is given in a companion paper in these proceedings.[1] Recently, the work of Hagelstein[2] has motivated an experimental program[3] to test the feasibility of pumping soft X-ray lasers with such a scheme. Trebes and Krishnan[4,5] have demonstrated UV fluorescence by the combined effects of optical pumping and collisional transfer. This paper presents experimental results of the simultaneous measurement of enhanced fluorescence on four different transitions in CII, corresponding to four distinct upper states, when only one of these states was optically pumped with AℓIII line radiation. Also presented are measurements and estimates of electron density and temperature in the C plasma as well as the Aℓ pump plasma. These measurements enabled the development of a multi-level, collisional-radiative model for CII. The experimental observations are discussed in light of the model. Prospects for building a UV laser are discussed.

Published in: Laser Techniques in the Extreme Ultraviolet (OSA, Boulder, Colorado, 1984), S.E. Harris and T.B. Lucatorto, Eds. (AIP, New York, 1984), p.387.

FLUORESCENCE MEASUREMENTS

This section begins by describing the experimental apparatus and characterizing the carbon discharge plasma. Then the measurements of fluorescence are described.

Figure 1 is a schematic diagram of the experimental apparatus. The carbon plasma is produced in a laser initiated vacuum arc, between the negative carbon cathode and a grounded carbon anode as shown. Two Co_2 TEA lasers are used. Laser I is focused on the cathode and triggers a vacuum arc discharge. The power supply for this discharge is a pulse-forming network with an external, impedance matching resistor. A typical oscillogram of discharge current vs time is shown in Fig. 2a. The flat-topped current duration is about 60 μs. Figures 2b, 2c, 2d, and 2e show typical line radiation vs time from lines of CI, CII, CIII, and CIV at wavelengths indicated on the figures. CI radiation is present only during the rising portion of the current pulse and after decay of the pulse. The CII and CIII radiation exhibits quasi-steady behavior, but the CIV intensity is seen to decrease during the latter portion of the discharge, although the current is constant. Such a decrease may be due to a decrease in electron temperature in the constant current arc, which in turn may be caused by dynamic effects. Based on these observations, it was decided to attempt optical pumping of the C plasma at a time of 40-45 μs after arc initiation, when quasi-steady conditions were observed.

The aluminum pump plasma was produced by focusing Laser II after the selected delay of typically 43 μs, onto an Aℓ rod target, shown in Fig. 1. To ensure reproducibility, the Aℓ rod was replaced after every ten laser shots. With each new target, five shots were fired to clean the target surface and then data were obtained with the next 5 shots. Earlier experiments[4,5] had shown that the 5d level in CII was pumped by AℓIII, 560.433 Å line radiation from the adjacent Aℓ laser produced plasma. Furthermore, the optical excitation was shown to be collisionally transferred to the 5f, higher angular momentum level. Enhanced fluorescence was measured on the 5d-3p and 5f-3d transitions at 2138 and 2993 Å, respectively. The primary motivation for the experiments described in this paper was to unravel the collisional-radiative kinetics in CII, following selective optical pumping. Toward this end, four different wavelengths in CII were monitored simultaneously. The wavelengths selected are shown in Fig. 3. The 2138 Å and 2993 Å lines were expected to show enhanced fluorescence due to optical pumping as before. The 3920 Å line would show fluorescence only if the 4s upper state were strongly coupled by collisions and radiative transitions to the 5d level. The 1335 Å line stems from an n = 2 level which is much lower in energy than the 5d and 4s levels. Furthermore, the $2p^2$ upper state of this line is not accessible by dipole, single electron transitions from the n = 5 or n = 4 shells. Therefore no fluorescence was expected at the

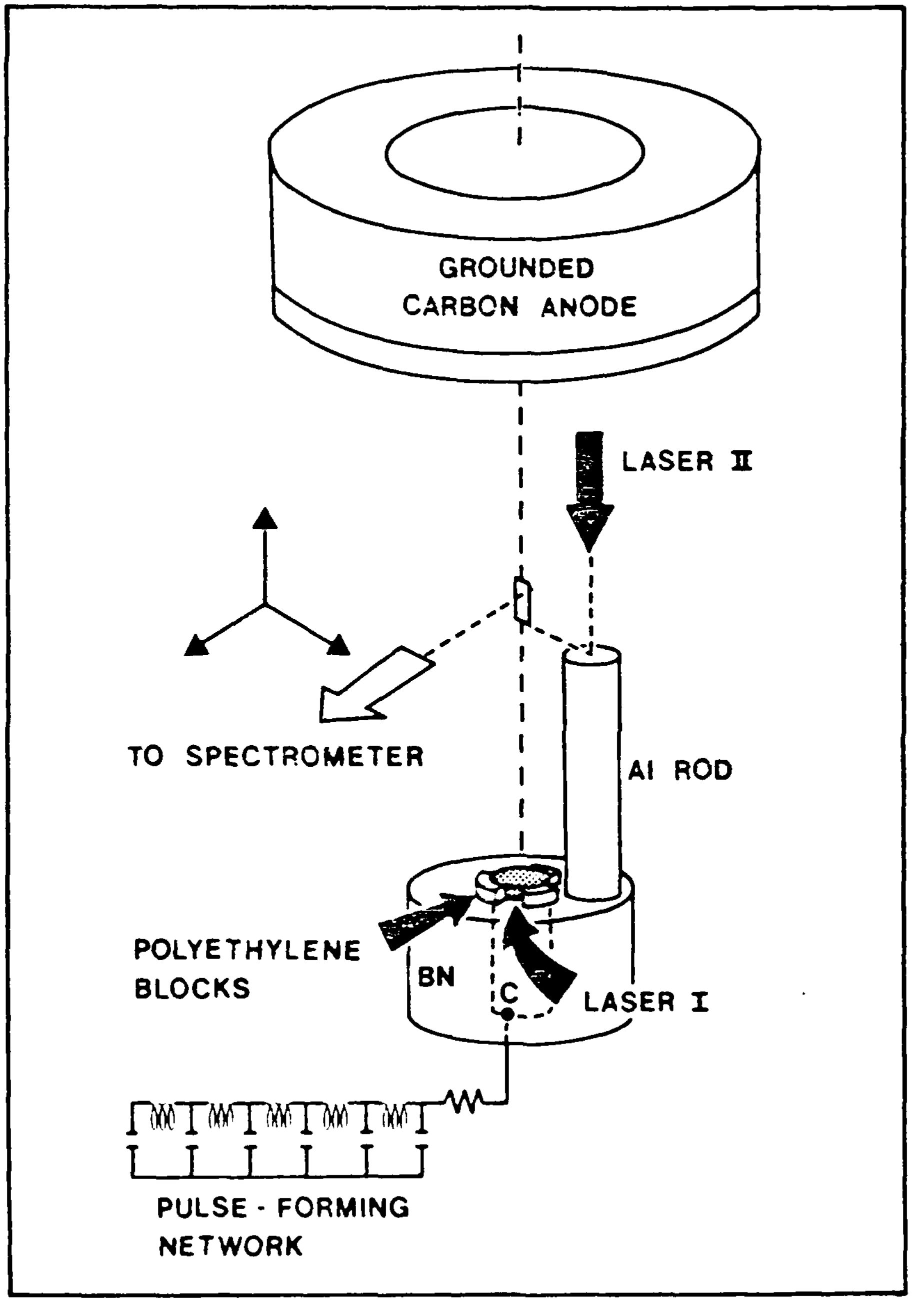


Fig. 1. Schematic diagram of the experimental apparatus.

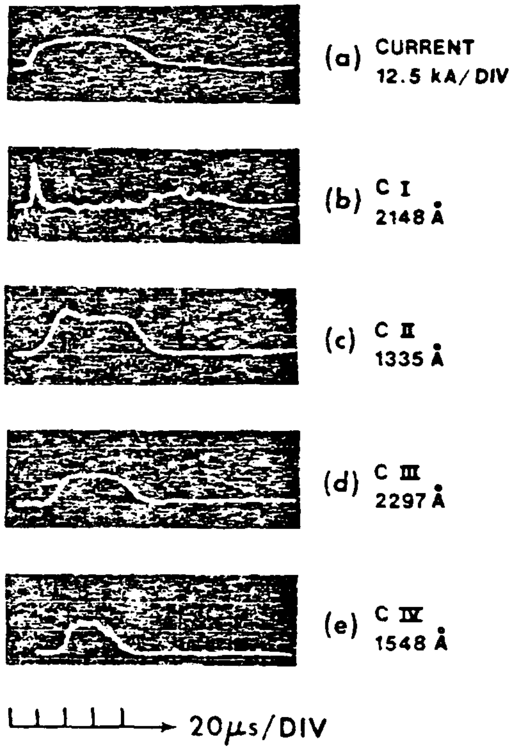


Fig. 2. Discharge current and carbon line emission vs time in the laser-initiated vacuum arc: a) Current 12.5 kA/DIV, b) CI, 2148 Å line intensity, c) CII, 1335 Å line intensity, d) CIII, 2297 Å line intensity, and e) CIV, 1548 Å line intensity. The time scale is 20 μs/DIV.

1335 Å wavelength.

Figure 4 shows a Grotrian diagram of AℓIII. A .25 m Jarrel-Ash monochromator was used to monitor the AℓIII, 3713 Å transition in the laser produced Aℓ plasma. This wavelength was chosen because direct measurement of the 5p-3s, 560 Å pump transition was hampered by inadequate resolution of the XUV spectrometer, as discussed later. It can be shown that the 5s upper state of the 3713 Å line and the 5p state are strongly coupled by collisions in an expanding, laser produced plasma.[6] Therefore the intensity of the 3713 Å line does provide a measure of the duration and relative intensity of the 560 Å pump line.

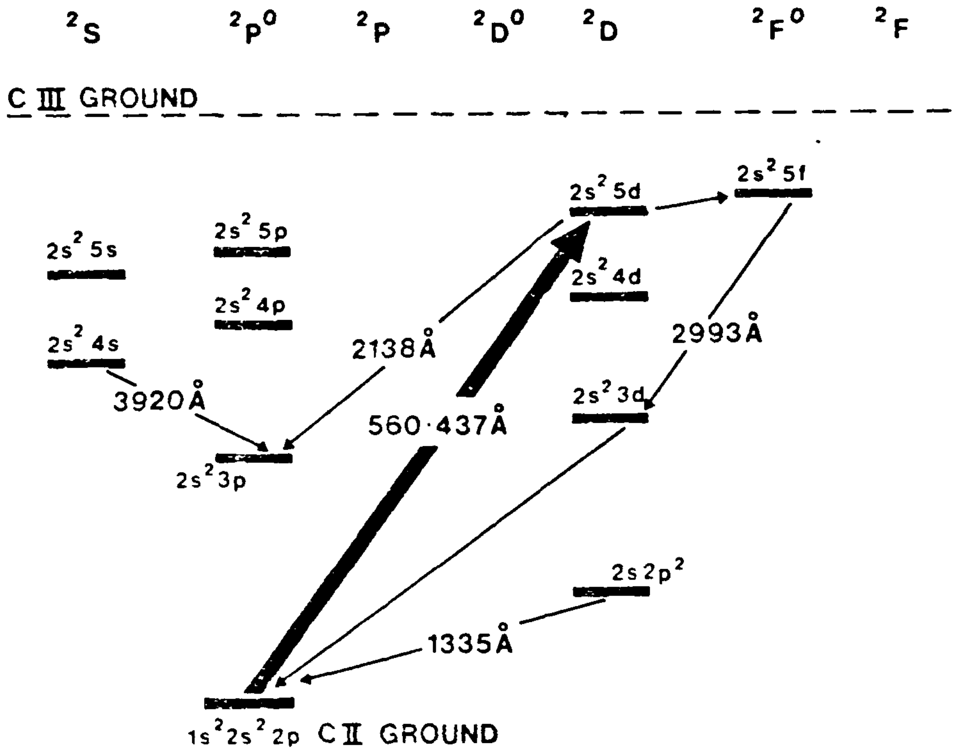


Fig. 3. Partial Grotrian diagram of CII, showing the wavelengths studied.

Figure 5 shows the arrangement of the spectrometers used to monitor the five wavelengths discussed above. All spectrometers, with the exception of the Jarrel-Ash, were focused onto the same local plasma region, 15 mm downstream of the cathode, along the discharge axis. The Jarrel-Ash was focused to a region 2 mm downstream of the Aℓ disc along the laser plasma axis.

In the first series of experiments, a fixed discharge current of 3.4 kA was arbitrarily chosen and the Aℓ plasma was produced 43 μs after discharge initiation. Ideally, the electron temperature in the carbon plasma should be such that the ground state population of CII is high, while the excited state population of the 5d level is low. Since it was difficult to directly measure the CII ground state population, the optimum discharge configuration was not established.

The observed fluorescence is shown in Fig. 6. Figure 6a shows three traces. The upper trace shows the CII, 2138 Å intensity, the middle trace the CII, 2993 Å intensity, and the lower trace the AℓIII, 3713 Å intensity vs time. Significant enhanced

To summarize the experimental measurements, optical pumping of CII with AℓIII line radiation was studied by examining simultaneously four different wavelengths in CII. Enhanced fluorescence was observed from the pumped 5d level as well as from the neighboring 5f level. In addition, fluorescence was also observed from the 4s and $2p^2$ levels. The 4s level was probably fed by collisions from the n = 5 shell whereas the $2p^2$ level was probably collisionally excited from the CII ground state by electrons from the laser plasma. The electron density in the C arc was measured to be 1.5×10^{15} cm^{-3}. The electron temperature was estimated to be 3.3 eV. The AℓIII, 560 Å pump line radiation was found to persist for up to 3 μs in the laser produced plasma. In the next section, the collisional-radiative kinetics of the optically pumped CII ions are examined. The experimental observations are compared with the model and the feasibility of pumping a laser using such a scheme is discussed.

COLLISIONAL-RADIATIVE KINETICS IN CII

Using the measured density and temperature as inputs, a collisional-radiative model was developed for CII. This model, described in detail in Trebes,[6] included for a given level: collisional excitation and de-excitation, collisional ionization, radiative and three-body recombination from the CIII ground state, and dipole allowed radiative transitions. The energy levels and some oscillator strengths were obtained from standard references.[11,12] Other oscillator strengths and various rate coefficients were obtained from Morgan.[13] The model developed allows calculation of the distribution of the populations in many levels, subsequent to the selective optical pumping of the 5d level. Some results are shown in Fig. 14. Figure 14a shows the energy levels, some allowed transitions and their radiative lifetimes in ns. From the radiative lifetimes indicated in Fig. 14a, it appears that the 5f-3d transition at 2993 Å is a potential candidate for a quasi-cw laser, since the 5f radiative lifetime is much longer than the 3d radiative lifetime. However, one major drawback is the strong coupling of the 3d lower level with the CII ground state, which can lead to optical trapping of the 3d-2p, 800 Å radiation. From the modified coronal model, the CII ground state density was estimated to be 6.7×10^{14} cm^{-3}, for the measured n_e and T_e. For this ground state density, the optical depth at line center of the transition is 27.2, for an assumed transverse plasma dimension of 1 cm. Using the Holstein escape factor,[14] the modified lifetime of the 3d level is 16 ns. Since this modified lifetime is still shorter than the radiative lifetime of the 5f level, quasi-cw lasing is possible, but if the transverse plasma dimension is higher or if the CII ground state density is slightly higher, then optical trapping increases the lifetime of the 3d level to a value higher than the 5f lifetime, thus destroying the possibility of a quasi-cw laser at 2993 Å. A second deleterious consequence of the rather high n_e and T_e in the carbon plasma is that collisional rates are high enough to tend to thermalize the n = 3, 4, and 5 shells in CII. Figure 14b shows the collisional ionization rates for the n = 5 levels, the collisional transfer rates between these levels, and some de-excitation rates for the transitions considered in Fig. 14a. From the figure, it is observed that the collisional transfer time from 5d to 5f is short compared to the 5d radiative lifetime. This is desirable in order to transfer the pumped electrons in the 5d to the 5f, potential upper laser level. However, the figure also shows that collisional ionization from the 5d and 5f levels proceeds as rapidly as the collisional transfer. Furthermore, the collisional de-excitation times for the 5d and the 5f levels are an order of magnitude or more shorter than the radiative lifetimes. This means that the optically pumped 5d population is rapidly distributed by collisions to the other levels in the n = 4 and 5 shells, as well as to higher lying levels and the CIII ground state. It is clear that conditions in the carbon plasma are not optimal for a 5f-3d laser, since selective optical pumping of the 5d level is not accompanied by collisional transfer exclusively to the 5f level. Another conclusion that may be drawn from the above analysis of collisional rates is that for a given strength of the optical pumping, enhanced fluorescence should be seen simultaneously on several transitions from the high lying levels of CII, since the collisional coupling times between levels are orders of magnitued shorter than the 3 μs duration of optical pumping. This conclusion is verified by the observed fluorescence at 3920 Å from the 4s level, discussed earlier.

The above discussion has revealed much of the kinetics of the CII ions without regard to the actual strength of the optical pump. Using the estimate of the lower bound of the AℓIII, 5p population of 1×10^{12} cm^{-3}, it is possible to estimate the degree of enhanced fluorescence expected from the pumped 5d level. With the CII ground state density of 6.7×10^{14} cm^{-3}, convolution of the AℓIII and CII Doppler line shapes and inclusion of the solid angle subtended by the observed volume to the Aℓ plasma yields[6] an expression for the lower bound of the optical pump rate:

$$\text{Pump Rate} = 9.7 \times 10^{11} \frac{1}{\sqrt{T_{A\ell}\, T_C}} L_{A\ell} \times \Delta\Omega \times n_{5p} \times A_{5p-3s} \quad I' \qquad (2)$$

where $T_{A\ell}$ and T_C are the ion temperatures of Aℓ and C, respectively, $L_{A\ell}$ is the effective Aℓ plasma dimension, ΔΩ the solid angle subtended by the pumped carbon volume to the Aℓ plasma, n_{5p} is the lower bound estimate of the AℓIII, 5p population, A_{5p-3s} is the 560 Å transition probability and I′ is a numerical estimate of the convolution integral of the two Doppler line shapes. For the conditions discussed throughout this paper, the lower bound of the pump rate is determined to be 10^{19} electrons/cm^3 s. For the 5d level, the sum of all possible collisional and radiative de-exci-

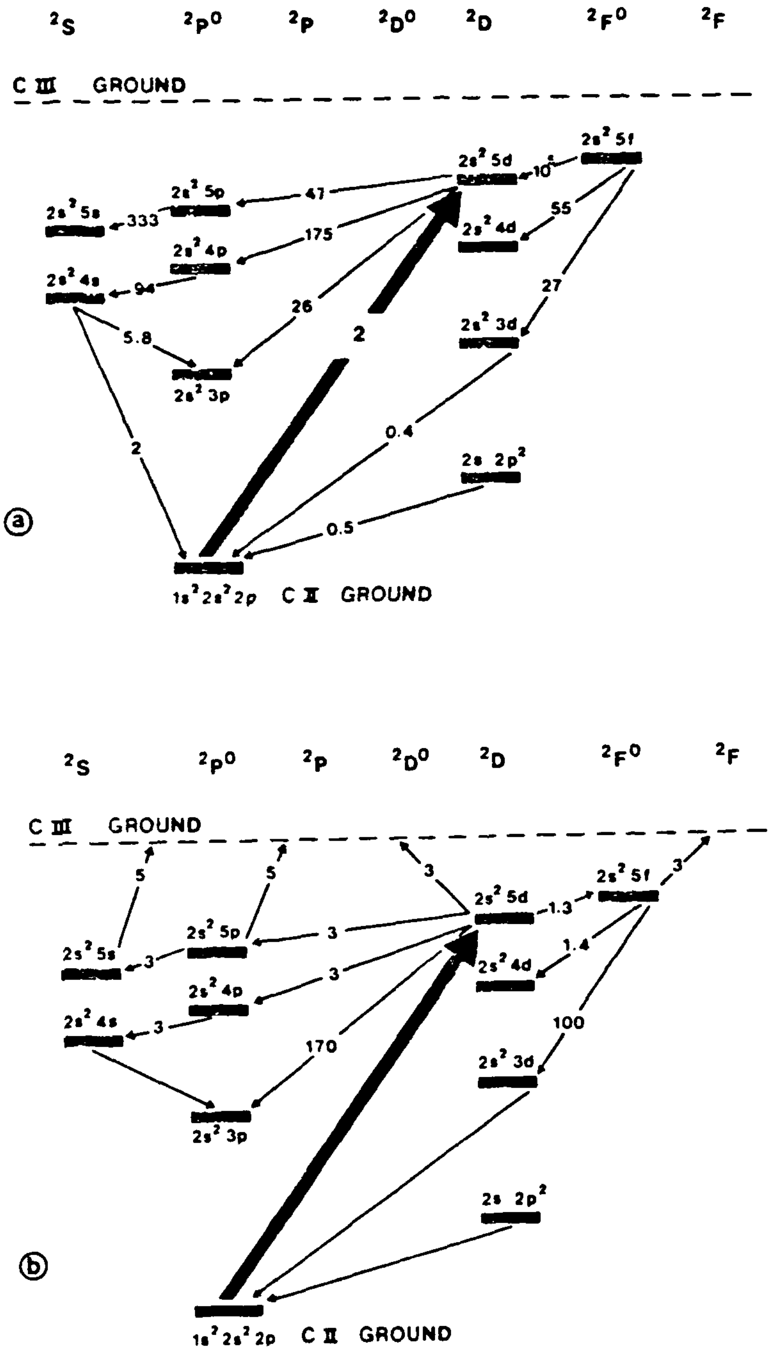


Fig. 14. Radiative and collisional times for transitions in CII. a) Radiative lifetimes (in ns) and b) collisional ionization and de-excitation times (in ns), for selected transitions in CII.

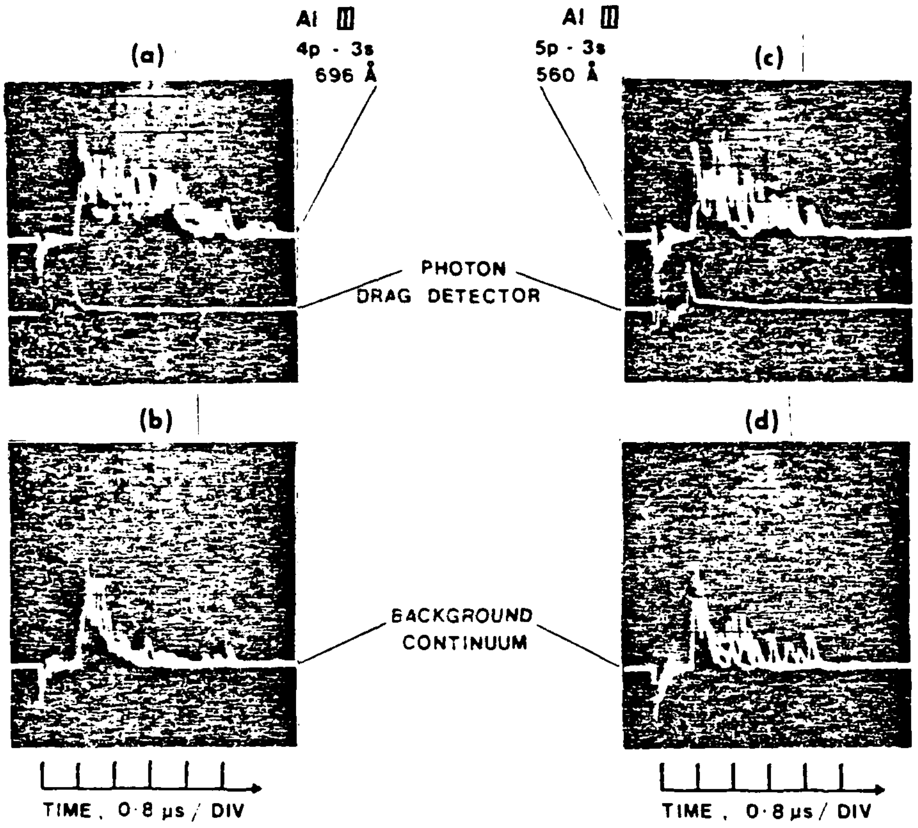


Fig. 13. Time-resolved AℓIII line intensities in laser produced plasma: a) AℓIII, 4p-3s, 696 Å intensity vs time; b) continuum background; c) AℓIII, 5p-3s, 560 Å intensity vs time; d) continuum background. The lower trace in a and c is the signal from the photon drag detector which samples the Co$_2$ laser.

ground continuum, measured 5 Å from line center. Figure 13c shows the 560 Å intensity vs time, and Fig. 13d shows the background continuum, 5 Å from line center. In each case, the figure shows a superposition of three laser shots on the photograph. The lower trace on Figs. 13a and 13c is the output of a photon drag detector which samples a portion of the Co$_2$ laser beam. Both 696 Å and 560 Å line radiation signals emerge above the continuum background for about 3 μs. This time duration is consistent with the observation of enhanced fluorescence also for 3 μs. In conclusion, the lack of an absolutely calibrated XUV spectrometer as well as the non-equilibrium expansion of the laser plasma made it impossible to accurately estimate the pump line intensity.

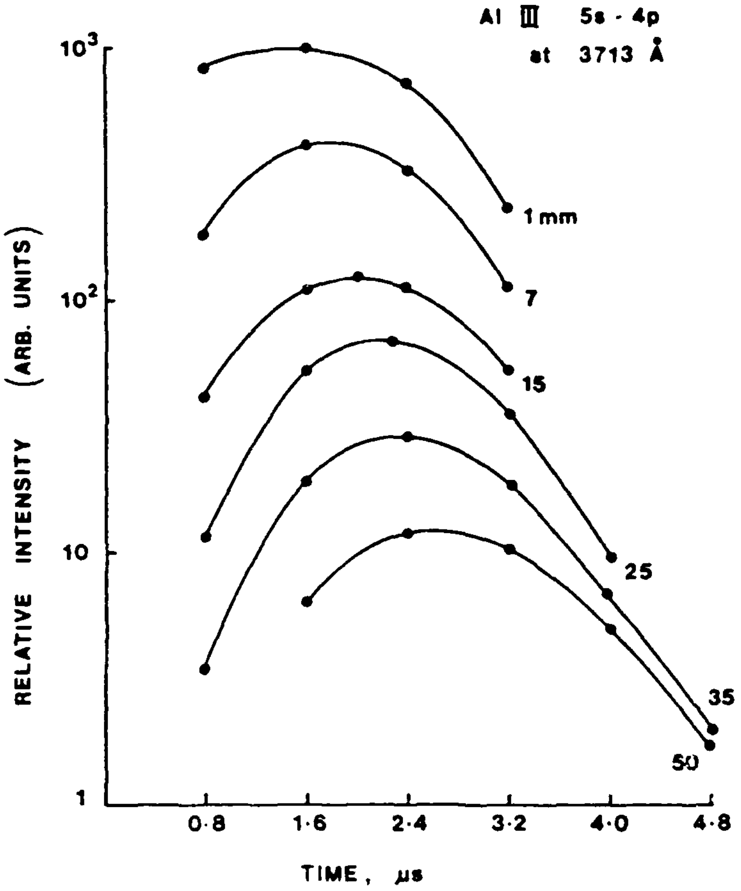
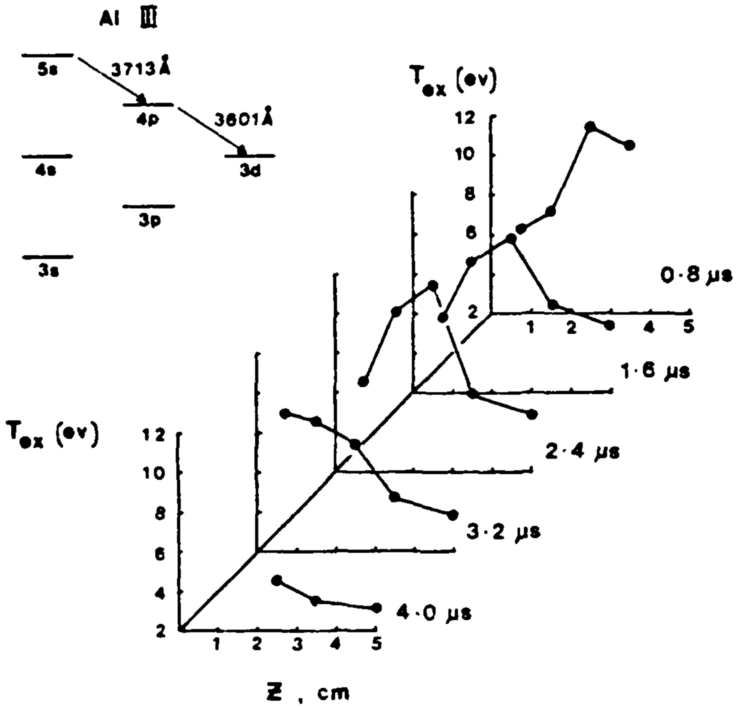


Fig. 12. AℓIII, 3713 Å line intensity vs time, for several axial positions downstream of the Aℓ target, along the target normal.

times in the plasma expansion is further verified in Fig. 12, which shows the AℓIII, 3713 Å intensity vs time, for several positions downstream. The intensity is highest for distances less than 3 cm at times less than 3 µs. The above detailed description of the AℓIII, 3713 Å line intensity indicates the presence of excited states of AℓIII in the rapidly expanding laser produced plasma. Direct measurement of the AℓIII, 560 Å line shape was not possible because the 1.5 Å resolution of the XUV spectrometer was about 150 times larger than the estimated Doppler width of the 560 Å line. Even to detect this line, therefore, the line intensity must be 150 times higher than that of the continuum background. Time-resolved intensity measurements of the 560 Å as well as the AℓIII, 4p-3s, 696 Å line are shown in Fig. 13. Figure 13a shows the 696 Å intensity vs time, while Fig. 13b shows the back-



EXCITATION TEMPERATURE IN Al LASER PRODUCED PLASMA FROM INTENSITY RATIO OF 3601 Å/3713 Å Al III LINES

Fig. 11. Excitation temperature derived from the AℓIII 3713/3601 Å line ratio plotted as a function of time and of distance downstream from the Aℓ target.

after the laser pulse, reaches a maximum and then decreases. This anomalous behavior persists for up to 3 μs at distances up to 3 cm downstream. The cause of this anomaly is optical trapping of the 3601 Å radiation which causes an increase in intensity of the 3601 Å line and results in an anomalously low temperature derived from the line ratio. At greater distances downstream and for later times in the expansion, the plasma density is sufficiently low that the 3601 Å line is optically thin and the derived temperature decreases with time as expected. The density of the 3d level required to give an optical depth of unity at 3601 Å is found to be 1 x 10^{13} cm^{-3}, for an ion temperature of 1 eV. With this lower bound, and assuming that the excitation temperature is 11 eV (based on the line ratios), the lower bound on the 5s and 5p densities is found to be 1 x 10^{12} cm^{-3}. For distances less than 3 cm and times shorter than 3 μs, the densities are clearly higher. The persistence of intense, AℓIII radiation for such long modified coronal equilibrium model.[1] The coronal equilibrium also gives a CII/CIII ground state ratio of 1 at the same temperature of 3.25 eV. The uncertainty in the measurement translates to a temperature uncertainty of ±0.25 eV. At the measured temperature of 3.25 eV, Fig. 10 shows that there is a negligible fraction of CIV in the plasma. At 3.4 kA, the resonance line of CIV at 1548 Å could not be detected.

To recapitulate, the carbon discharge plasma was found to have an electron density of 1×10^{15} cm^{-3} and an electron temperature of 3.25 ± 0.25 eV. Under these conditions, the n = 5 levels of CII are in thermodynamic equilibrium with the CIII ground state, thus causing the optical excitation of the 5d level to be rapidly distributed by collisions over a large number of higher levels. Population inversions and lasing on the 5d-3p and 5f-3d transitions are therefore difficult to achieve. In the next section, the Aℓ pump plasma is examined with a view to estimating the 560 Å pump line intensity.

PUMP LINE INTENSITY

In these experiments, it was not possible to measure directly the density and temperature of the laser produced plasma or to measure the absolute intensity of the pump transition. However, some measurements were made which together with numerical modeling allowed a reasonable estimate to be made of the 560 Å pump radiation. The initial temperature of the Aℓ plasma was determined by using an empirical relation[9] based on the laser focal spot intensity on the Aℓ target. The temperature was found to be ~10 eV. The initial density at a distance of 0.1 mm downstream of the target surface was estimated as 5×10^{18} cm^{-3}, based on measurements of Tonon and Rabeau[10] in a similar plasma. At this density and temperature, the modified coronal model[1] predicts that most of the ions will be in charge states higher than AℓIII. The AℓIII must therefore be formed in the expansion phase of the laser produced plasma. This expansion leads to a rapid decrease in density and temperature, such that "freezing" of the populations occurs, with the resultant charge state distribution characterized by an effective temperature which is much higher than the local electron temperature. Such a non-equilibrium expansion makes it hard to interpret spectroscopic measurements in the expansion phase of the plasma.

One approach to determining the temperature was by measuring the relative intensity of the 3713 Å, 5s-4p and 3601 Å, 4p-3d transitions in AℓIII (see Fig. 4). If the collisional coupling rates between the 5s and 4p levels greatly exceed the radiative rate, then the two levels are in collisional equilibrium and the 3713/3601 line ratio yields an excitation temperature for AℓIII. It is shown[6] that this is the case for $n_e > 1 \times 10^{16}$ cm^{-3}. The excitation temperatures obtained as a function of time at various axial positions downstream of the target surface are plotted in Fig. 11. Curiously, the temperature appears to increase well mination of the ratio of the ground level populations of CII and CIII, as a function of temperature. Independently, a modified coronal equilibrium calculation also yields the ratio of the ground level populations of CII and CIII, as a function of temperature. The intersection of these two independent functions then yields the electron temperature. The transitions chosen were at 2478 Å in CI and 2993 Å in CII. The measured intensity ratio of 2993/2478 was 27, at 50 μs after discharge initiation. This ratio corresponds to a CII/CIII ground state ratio of 1, at a temperature of 3.25 eV. Figure 10 shows the relative abundance of the different carbon charge states vs temperature, as derived from the

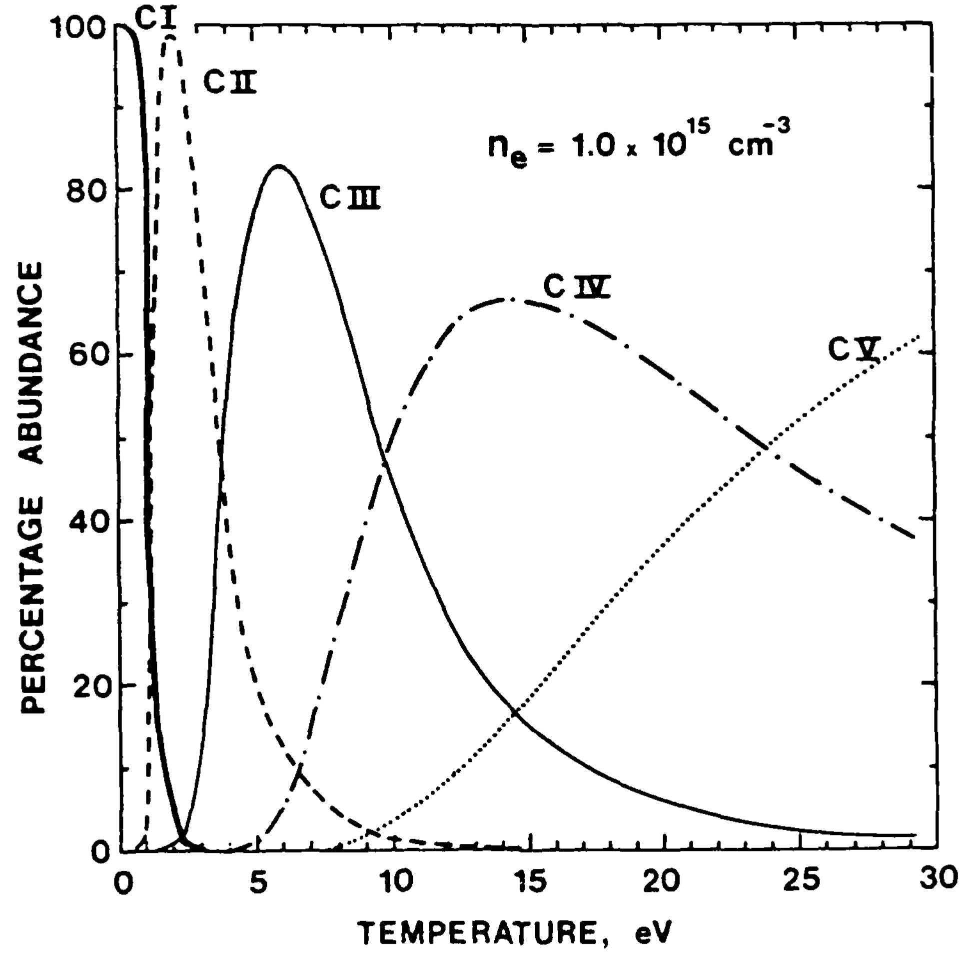


Fig. 10. Relative abundance of C charge states vs temperature, obtained from a modified coronal equilibrium calculation. $n_e = 1 \times 10^{15}$ cm^{-3}.

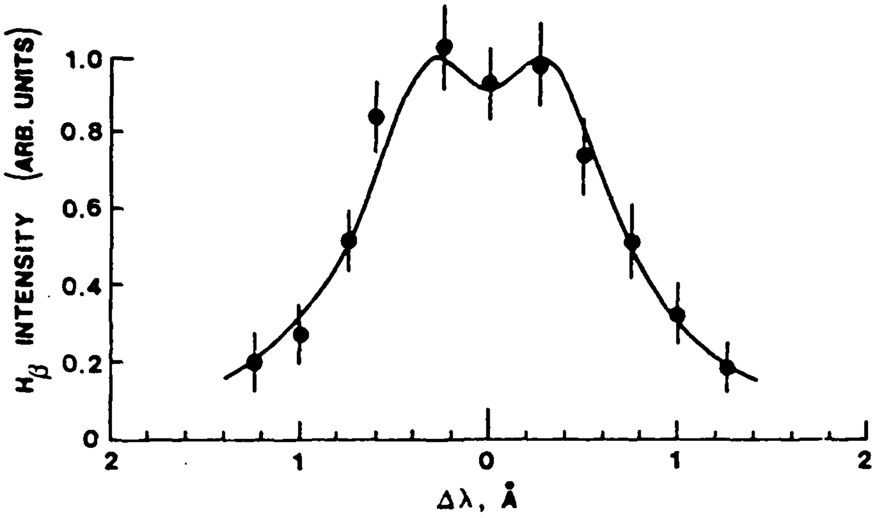


Fig. 9. H_β line intensity vs wavelength in the C discharge. The curve through the measured points is a convolution of a Stark profile with a Doppler profile.

ducible data were obtained by cleaning the entire cathode assembly after every 30 shots. The measured H_β line intensities at 3.4 kA, at 50 μs after arc initiation are shown in Fig. 9. The curve through these points is a best fit of a Stark profile,[8] convoluted with a Doppler profile. The density obtained is 6×10^{14} cm^{-3}, for a best fit temperature of 0.4 eV. The dip at the center of the Stark profile is a sensitive measure of temperature, because of the convolution of the Doppler profile. For example, a higher assumed temperature of 1 eV would completely wash out the dip. In the next section it will be shown that the temperature in the C arc on the axis is about 3 eV. Modified coronal calculations show that the H_β intensity is very sensitive to temperature.[6] It would appear therefore that the measured H_β signals originated predominantly from outer regions of the arc, where the temperature is lower. The measured density of 6×10^{14} cm^{-3} is thus a lower bound and consistent with the earlier estimate of 1.2×10^{15} cm^{-3}, from the scaling law of Keren and Hirshfield.[7]

ELECTRON TEMPERATURE MEASUREMENT

At densities of ∿1 x 10^{15} cm^{-3} and temperatures of ∿3 eV, it can be shown[6] that high lying levels of CI and CII are in thermodynamic equilibrium with the ground levels of CII and CIII, respectively. Measurement of the relative intensities of transitions from such higher levels in CI and CII thus leads to a deter-

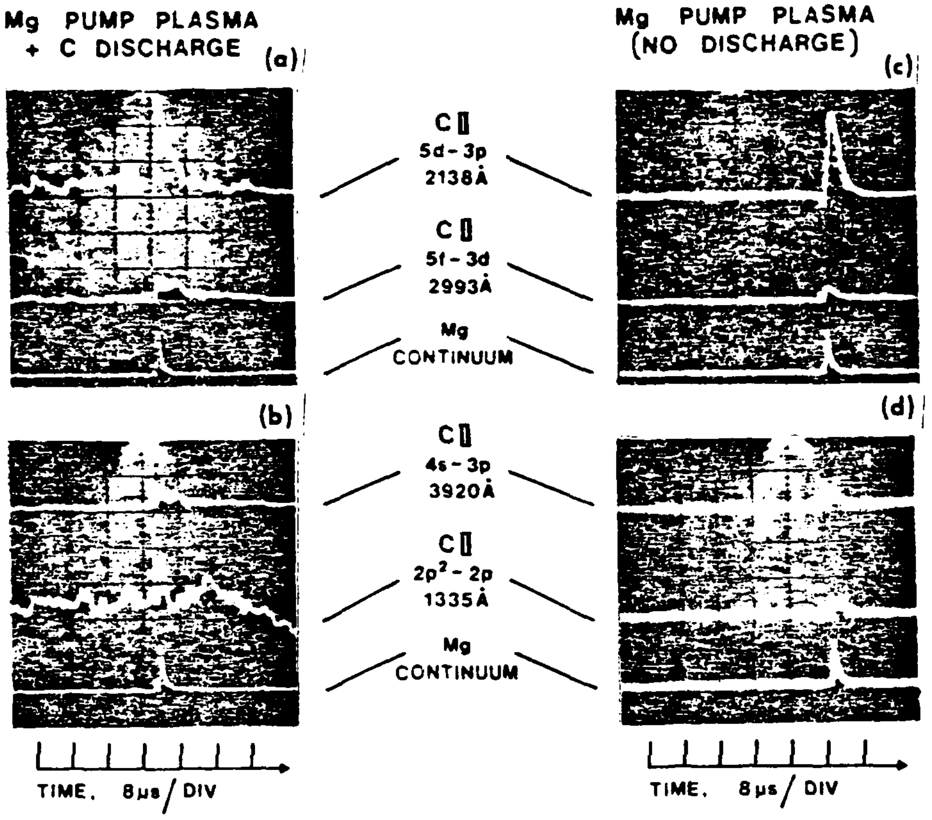


Fig. 8. C discharge with an adjacent Mg laser produced plasma: a) intensity vs time of CII, 2138 and 2993 Å lines, and AℓIII, 3713 Å line; b) intensity vs time of CII, 3920 and 1335 Å lines, and AℓIII, 3713 Å line. 8c) and d) same lines as in a and b, but with no C discharge, to show spurious background signals due to Mg laser produced plasma alone.

3.4 kA. To corroborate this estimate, hydrogen atoms were introduced into the arc and the Stark width of the H_β line was measured. The hydrogen was introduced by arranging three segments of polyethylene on the surface of the boron nitride insulator (Fig. 1). The 2 m Ebert spectrometer was used for these measurements, with a resolution of 0.2 Å. The Stark profile was measured by scanning a photomultiplier across the focal plane at 0.2 Å intervals. Ten shots were fired at each wavelength and the average line intensity was recorded. To ensure reproducibility of the data, the Ly_α, 1216 Å line intensity and the CII, 1335 Å line intensity were monitored simultaneously with the H_β signal. Repro-

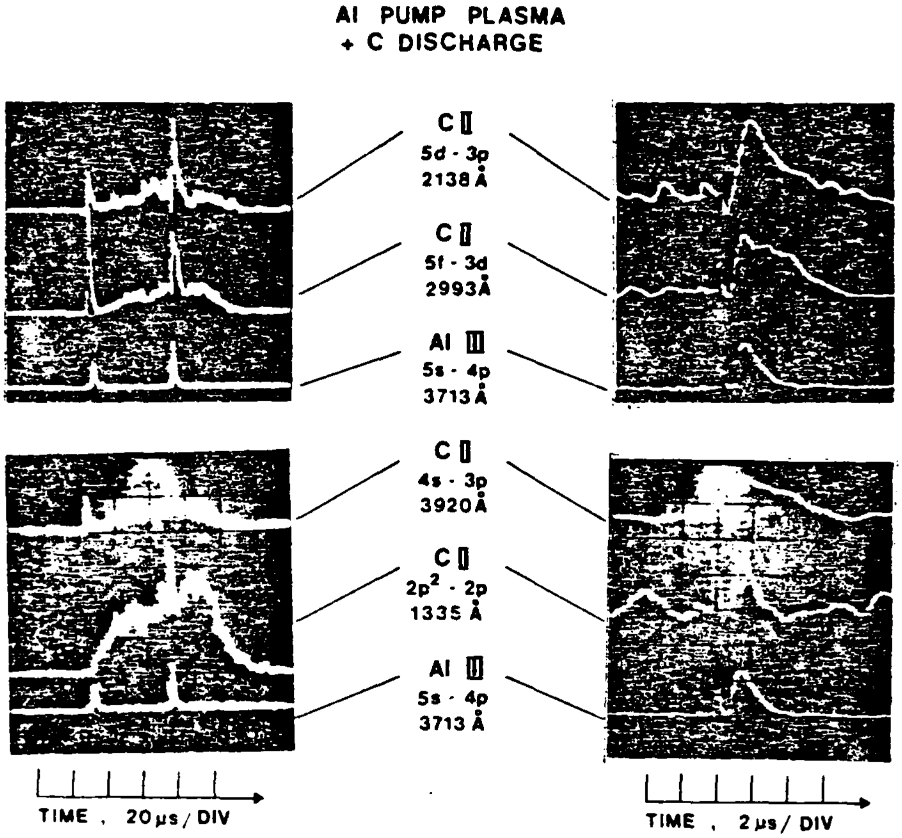


Fig. 7. Data of Fig. 6a and 6b displayed on two timescales of 20 μs/DIV and 2 μs/DIV, respectively.

ELECTRON DENSITY MEASUREMENT

Electron density in a laser-initiated carbon vacuum arc similar to that used in these experiments was measured by Keren and Hirshfield,[7] by measuring the refraction of a far-infrared laser beam after propagation through the plasma. For a cathode identical to that used here, but with the vacuum vessel walls serving as anode, n_e was measured for discharge currents I from 2 to 8 kA. The measurements were fit to a power law dependence on current, viz.:

$$n_e = 3 \times 10^{14}\, I^{1.9} \cos\phi / r^{2.4} \qquad (1)$$

where: r is the radius in cm and ϕ is the angle from the discharge axis. For a radius of 1.5 cm in these experiments, the above formula gives a density on axis of 1.2×10^{15} cm^{-3}, for a current of

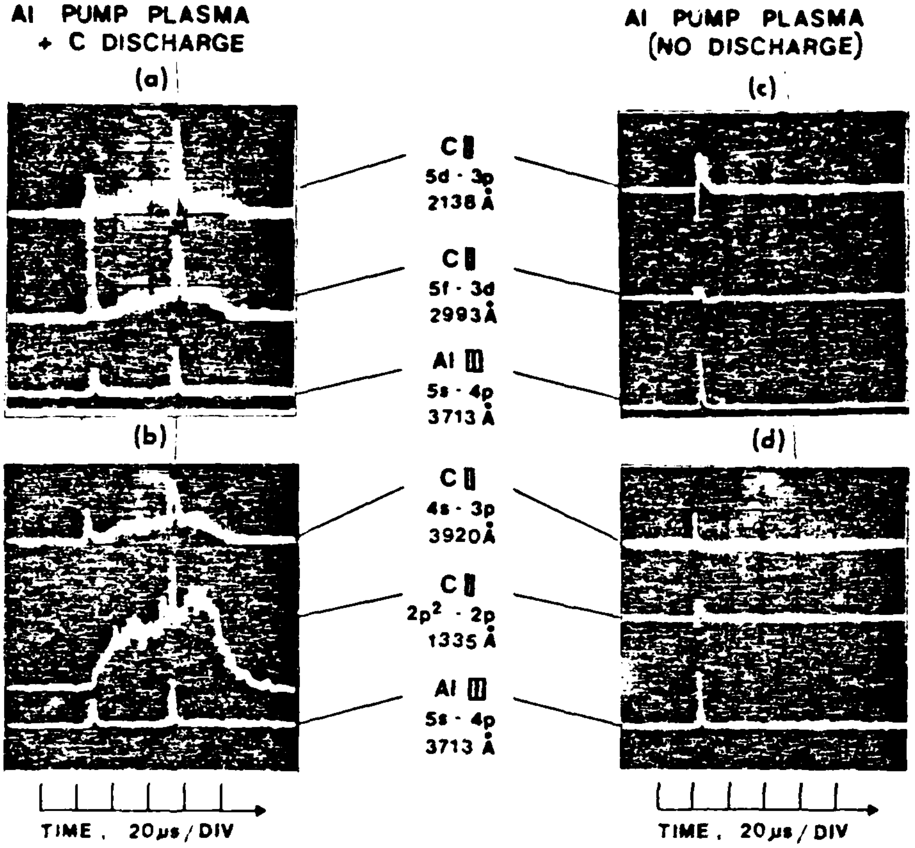


Fig. 6. Optically pumped fluorescence in CII: a) intensity vs time of CII, 2138 and 2993 Å lines, and AℓIII, 3713 Å line; b) intensity vs time of CII, 3920 and 1335 Å lines, and AℓIII, 3713 Å line. 6c) and d) same lines as in 6a and b, but with no C discharge to show spurious background signals due to Aℓ laser produced plasma alone.

from each other.

The preceding discussion has shown that in the carbon discharge, selective optical pumping to the 5d level is accompanied by strong coupling of the pumped level to other levels in the $n = 5$ and $n = 4$ shells. It is possible that the $n = 3$ levels are also coupled to higher levels. Such coupling is not conducive to producing population inversions at the 2138 and 2993 Å UV wavelengths. A detailed, collisional-radiative model must be constructed to examine such coupling. Necessary inputs to such a model are the electron density n_e and electron temperature T_e in the carbon plasma. Experiments were performed to measure these parameters. The results are described in the next two sections.

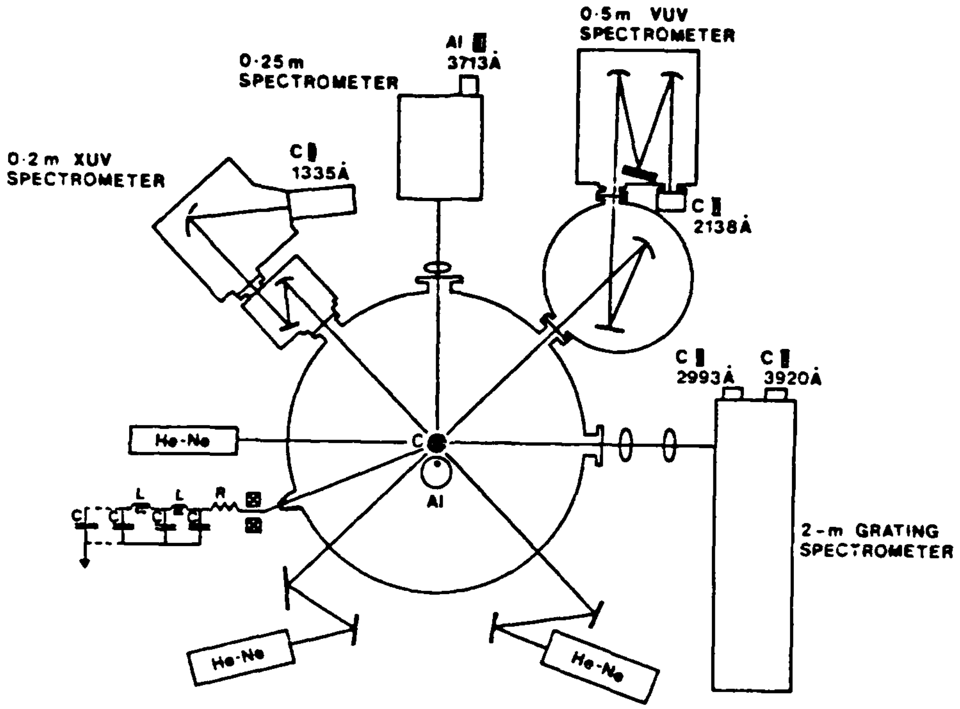


Fig. 5. Schematic diagram of the spectrometer arrangement.

for the 1335 Å fluorescence as compared with that for each of the other three wavelengths. Figure 7 shows the data of Fig. 6 on two timescales, 20 μs/DIV and 2 μs/DIV. The 1335 Å fluorescence is seen to decay more rapidly than the other lines. To test this conjecture, the Aℓ rod target was replaced with a Mg rod and the experiments were repeated. Since no lines of Mg are coincident with any CII transitions, no optical pumping was expected. Figure 8 shows the results. Figure 8a shows the time evolution of the CII, 2138, 2993, and AℓIII, 3713 Å line radiation. Figure 8b shows the CII, 3920, 1335, and AℓIII, 3713 Å lines. As with Fig. 6, the background measurements are shown in Figs. 8c and 8d. It is seen from the figures that although there appears to be some enhanced fluorescence coincident with a Mg pump plasma, the apparent enhancements on all but the 1335 Å line are in fact due to spurious background. The rather large background at 2138 Å is probably due to the wings of a bright, MgIII line at 2135 Å. The 1335 Å line shows enhanced fluorescence clearly above the background, suggesting that for both the Aℓ and Mg plasmas, this transition was probably excited by electrons penetrating the C discharge from the laser produced plasma. Further work is needed to confirm this. Nevertheless, these results serve to underscore the point made in earlier papers[4,5] that optical pumping with line radiation is best achieved by using two separate plasmas which are well isolated

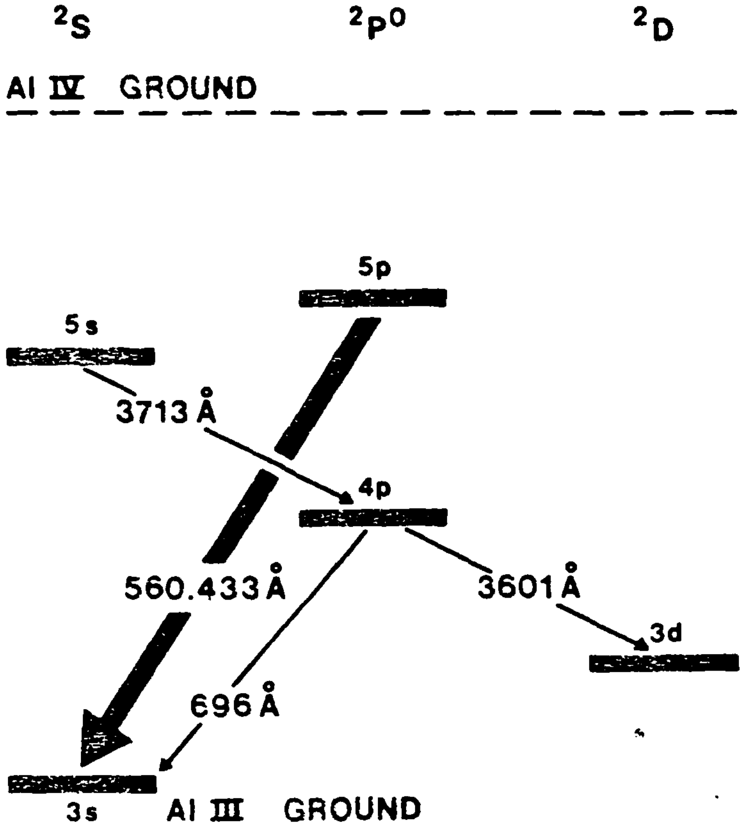


Fig. 4. Partial Grotrian diagram of AℓIII.

fluorescence is observed on both CII lines, coincident with the Aℓ plasma. Figure 6b shows the CII, 3920 Å intensity (upper trace) and the CII, 1335 Å intensity (middle trace) vs time. The lower trace is again the AℓIII, 3713 Å intensity. It is observed that both of these CII wavelengths also show enhanced fluorescence due to the Aℓ plasma. To ensure that the observed fluorescence was not due to continuum or to the wings of neighboring Aℓ lines from the Aℓ plasma leaking into the spectrometers, the experiments were repeated with no carbon discharge and only the Aℓ laser produced plasma. The results are shown in Figs. 6c and 6d. Some spurious background does appear, but the observed fluorescence in Figs. 6a and 6b is larger than this background for all four wavelengths.

The observed fluorescence at 1335 Å was puzzling, since the $2p^2$ upper state is not directly coupled to the upper levels. However, this state is strongly coupled to the CII ground state by a dipole allowed transition. It was possible that electrons from the denser and hotter Aℓ plasma collisionally excited this transition. This conjecture was supported by the different time scale tation rates as well as the collisional ionization rate is 10^{10} s^{-1}. Thus the steady state population enhancement of the 5d level by optical pumping is 10^8 cm^{-3} or higher. In the absence of optical pumping, the 5d population is estimated from the collisional-radiative model to also be about 10^8 cm^{-3}. These estimates imply that the enhanced fluorescence should be comparable to the spontaneous emission from the 5d level. If the pump line intensity is up to a factor of ten higher than the estimated lower bound, the enhanced fluorescence should then be a factor of ten above the spontaneous emission. In the earlier measurements[4,5] and in this work, the observed fluorescence was always between one and ten times the spontaneous emission, in agreement with the predictions of the model. In addition, the model predicts that the degree of enhancement at the 2993 Å wavelength should be lower than that at 2138 Å, since only a fraction of the enhanced 5d population is transferred to the 5f level. This is also in agreement with the experimental observations.

To summarize, a detailed examination of the collisional-radiative kinetics in CII has revealed that the density and temperature in the carbon plasma are far from ideal for creating a population inversion. Collisions dominate the kinetics and cause strong coupling between the n = 3, 4, and 5 levels, as well as higher levels. Thus, although the optical pumping is selective, the pumped population is dispersed over many channels.

CONCLUSION

A detailed experimental and theoretical study has been made of optical pumping in CII ions using AℓIII line radiation. This study has shown that although the optical pumping itself is selective, the pumped 5d population in CII is dispersed into many competing channels by collisional and radiative processes. Also, the strong collisional coupling between levels in the n = 3, 4, and 5 shells renders it difficult to sustain an inversion between 5f and 3d, a potential laser transition. Optical trapping also increases the 3d lifetime and further contributes to spoiling the chance for an inversion. These deleterious effects may be alleviated somewhat by a better choice of density and temperature for the carbon plasma. For example, as n_e is reduced, the collisional rates for various decay channels out of the 5d level are all proportionally reduced. For $n_e \simeq 10^{13}$ cm^{-3}, the 5d-5f electron collisional transfer time is 300 ns, which is still short compared to the optical pumping duration of 3 μs. For transitions within a given shell, particularly when the energy gap is very small compared to the temperature, the ion collisional transfer rate can sometimes exceed the electron collisional rate. For the 5d-5f transition, ion collisions are more important than electron collisions.[6] Thus the collisional transfer time is even less than 300 ns. At this n_e, 5d-3p radiative decay is ten times as rapid as collisional ionization or collisional de-excitation. If the collisional transfer time from 5d-5f is comparable with the 5d-3p radiative decay, up to 50% of the optically pumped 5d population may be transferred to 5f. Also, at this lower n_e, the CII ground state density is lower, and optical trapping of the 3d level is avoided. Finally, the 5f-3d radiative decay is then five times as rapid as collisional de-excitation via 5f-4d. Therefore a population inversion may be produced between 5f and 3d. It is important to point out that although the CII ground state density is only 6.7×10^{12} cm^{-3}, if only 10% of the ground state is optically pumped to the 5d level, then the 5f population would be about 3.0×10^{11} cm^{-3}. At 2993 Å, this corresponds to a small signal gain of .1 cm^{-1}. If the gain medium is 10 cm in length, the resultant net gain is quite sufficient to sustain oscillation in a cavity.

In retrospect, the CII-AℓIII combination was chosen because of the good coincidence between the pump and absorption line wavelengths. In these experiments, the plasma conditions were not optimized for lasing. The CII plasma was too dense and hot, while the AℓIII pump species were produced in the non-equilibrium expansion of a laser produced plasma under conditions far from ideal for maximizing the pump line intensity. Nevertheless, some enhanced fluorescence was observed, with only 1×10^{-6} of the CII ground state being pumped to the 5d level. Under optimized conditions, 10% or more of the ground state population may be pumped to the 5d level and a very high gain laser is possible. These arguments are tempered by the observation that the major stumbling block of this particular ion combination is the unfavorable energy level structure of the CII ion. Firstly, the pumped 5d level is too close to the CIII ground state and thus readily ionized. Secondly, the n = 4 levels are close to the n = 5 levels and strongly coupled to them by superelastic collisions. Finally, since the 3d lower level of the potential laser transition is directly coupled to the ground state, optical trapping is a serious concern. A better approach to producing a laser using optical pumping with line radiation would consider both the line coincidences as well as the atomic level structure of the pumped ion. Just such considerations have led to the proposal of a new class of optically pumped lasers in Be-like ions. These schemes are described in a companion paper in these proceedings.[1]

ACKNOWLEDGMENTS

We are grateful to Dr. W.L. Morgan and to Dr. R.D. Cowan for providing atomic data on CII and AℓIII. This research is supported by the Air Force Office of Scientific Research (Grant # 81-0077).

REFERENCES

1. M. Krishnan and J. Trebes, these proceedings.
2. P. Hagelstein, Ph.D Thesis, "Physics of short wavelength laser

design," Lawrence Livermore Laboratory Report URCL-53100 (1981).

3. D.L. Matthews, P. Hagelstein, E.M. Campbell, A. Toor, R.L. Kauffman, L. Koppel, W. Halsey, D. Phillion, and R. Price, IEEE J. Quant. Elect. QE-19, 1786 (1983).
4. J. Trebes and M. Krishnan, Phys. Rev. Lett. 50, 679 (1983).
5. J. Trebes and M. Krishnan, IEEE J. Quant. Elect. QE-19, 1870 (1983).
6. J. Trebes, Ph.D Thesis, Yale University, unpublished.
7. H. Keren and J.L. Hirshfield, Appl. Phys. Lett. 36, 128 (1980).
8. H. Greim, Plasma Spectroscopy (McGraw Hill, New York, 1964), p. 270.
9. A. Montes, M. Hubbard, C. Kler, and I.J. Spalding, Appl. Phys. Lett. 36, 652 (1980).
10. Tonon and Rabeau, Plasma Physics 15, 871 (1973).
11. S. Bashkin and J.O. Stoner, Atomic Energy Levels and Grotrian Diagrams, Vols. I and II (North Holland Publishing Co., New York, 1975, 1978).
12. J. Reader, et al., "Wavelengths and Transition Probabilities for Atoms and Ions," NSRDS - NBS, 68 (1980).
13. Dr. W.L. Morgan, personal communication.
14. T. Holstein, Phys. Rev. 72, 1212 (1947).

Proposed new class of optically pumped, quasi-cw, ultraviolet and extreme ultraviolet lasers in the Be isoelectronic sequence

Mahadevan Krishnan and James Trebes
Yale University, New Haven, Connecticut 06520

(Received 20 February 1984; accepted for publication 10 May 1984)

Intense line radiation from plasmas of Mn VI, P IX, Al V, Al VIII, Al IX, and Al XI may be used to selectively pump population inversions in plasmas of C III, N IV, F VI, Ne VII, Na VIII, and Mg IX. Quasi-cw lasing is possible on $4p$–$3d$ and $4f$–$3d$ transitions at wavelengths 2177–230 Å. At the extreme ultraviolet wavelengths, 1-J, 10-ns laser output pulses at 10^8 W power levels are shown possible with existing discharge and laser technology.

Optical pumping with line radiation uses intense line radiation from a source medium to selectively pump a nearly coincident transition from the ground state in an adjacent medium. Population inversions are then possible between the pumped level and other intermediate levels. Fluorescence and lasing have been demonstrated at infrared and visible wavelengths using such selective optical pumping.[1–3] Ultraviolet (UV) fluorescence using pumping with extreme ultraviolet (XUV) line radiation has recently been demonstrated.[4,5] Soft x-ray laser schemes have also been proposed[6,7] and studied experimentally.[8] This letter describes a proposed new class of optically pumped, quasi-cw, UV and XUV lasers in six ions of the Be isoelectronic sequence. The possible wavelengths range from 2177 to 230 Å in C III, N IV, F VI, Ne VII, Na VIII, and Mg IX. In Be-like ions, the $4p$–$3d$ and $4f$–$3d$ transitions have favorable lifetime ratios for sustaining cw laser oscillation. Selective population of the $4p$ and $4f$ states could thus lead to a new class of UV and XUV lasers not considered earlier. This letter describes how intense line radiation from an ion species in one plasma may be used to resonantly pump Be-like ions in an adjacent plasma from the $2s^2\ {}^1S$ ground state to the $2s4p\ {}^1P^0$ upper state. Lasing is then possible on the $4p\ {}^1P^0$–$3d\ {}^1D$ transition, with the $3d$ lower level decaying rapidly to the $3p$ and $2p$ levels. Figure 1 shows the relevant energy levels in C III. At appropriate electron densities and temperatures in the Be-like plasmas, collisions rapidly transfer the $4p\ {}^1P^0$ excitation to the $4p\ {}^3P^0$ and the $4d$ and $4f$ levels. Lasing is therefore also possible on the $4p\ {}^3P^0$–$3d\ {}^3D$ and $4f$–$3d$ (singlet and triplet) transitions, as shown in Fig. 1. Table I lists selected optical pumps for ions of the Be-like isoelectronic sequence. In each pump ion the pump transition is optically allowed and terminates on one of the ground state configurations,[9] allowing for the creation of an optically thick and intense pump line. Table I also lists selected laser wavelengths from $4p$–$3d$ and $4f$–$3d$ transitions.

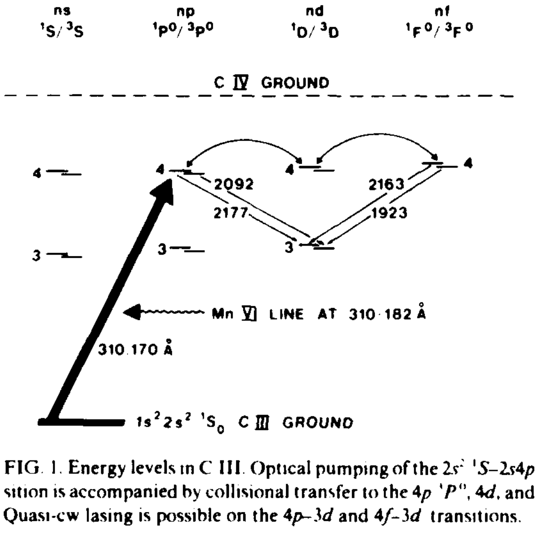


FIG. 1. Energy levels in C III. Optical pumping of the $2s^2\ {}^1S$–$2s4p\ {}^1P^0$ transition is accompanied by collisional transfer to the $4p\ {}^1P^0$, $4d$, and $4f$ levels. Quasi-cw lasing is possible on the $4p$–$3d$ and $4f$–$3d$ transitions.

Optical pumping with line radiation is best achieved by using two distinct plasmas, with only line radiation at a selected frequency propagating from the pump plasma into the pumped, lasing medium. Careful design of the plasma production scheme is necessary to avoid collisional and other interactions, which can spoil the selectivity of the optical pumping and destroy the inversion. Laser produced plasma designs[8,10] for soft x-ray lasers in He and H-like ions have produced plasmas with densities, temperatures, and ionization levels equal to or greater than those required for the schemes proposed here. High voltage pulse discharges[11,12] are also suitable media. Specific experimental configurations are described in detail elsewhere.[13] This letter focuses on the physics of the optical pumping and shows that high gain, long pulse lasers from UV to XUV wavelengths are possible with existing laser and pulse discharge technology.

In general, the two plasmas require distinctly different densities and temperatures. The pump ion density and temperature must be high enough to maximize the pump line intensity and overcome the wavelength mismatch between the pump and absorption wavelengths by Doppler broadening. The temperature and density of the pumped plasma

TABLE I. Optical pumps for the $2s^2\ {}^1S$–$2s4p\ {}^1P^0$ transition in Be-like ions, and typical wavelengths of possible laser transitions, $4p$–$3d$ and $4f$–$3d$.

Laser species	$2s^2$–$2s4p$ wavelength (Å)	Pump ion	$4p$–$3d$ laser wavelength (Å)	$4f$–$3d$ laser wavelength (Å)
C III	310.17	Mn VI	2177	2163
N IV	197.23	P IX	1284	1079
F VI	99.203	Al V	554	513
Ne VII	75.765	Al VIII	404	360
Na VIII	59.759	Al IX	308	285[a]
Mg IX	48.34	Al XI	250[a]	230[a]

[a] Scaled hydrogenically.

0003-6951/84/150189-03$01.00

DESIGN CONSIDERATIONS FOR OPTICALLY PUMPED, QUASI-CW, UV AND XUV LASERS IN THE Be ISOELECTRONIC SEQUENCE

Mahadevan Krishnan and James Trebes
Yale University, New Haven, Connecticut 06520

ABSTRACT

Intense line radiation from plasmas of MnVI, PIX, AℓV, AℓVIII, AℓIX, and AℓXI may be used to selectively pump population inversions in plasmas of Be-like CIII, NIV, FVI, NeVII, NaVIII, and MgIX. Quasi-cw lasing is possible on 4p-3d and 4f-3d transitions at wavelengths from 2177 Å to 230 Å. At the XUV wavelengths, 1 J, 10 ns laser output pulses at 10^8 W power levels are shown possible with existing discharge technology. Since all six laser ions are in the Be isoelectronic sequence, detailed studies of the optical pumping process at UV wavelengths in CIII would provide scaling parameters for the less accessible XUV wavelengths.

INTRODUCTION

The concept of optical pumping with line radiation predates the invention of the laser by three decades.[1,2] Optical pumping with line radiation uses intense line radiation from a source medium to selectively pump a nearly coincident transition from the ground state to an excited state in an adjacent medium. The pumped level may then be inverted with respect to lower levels. In 1930, Boeckner[2] described fluorescence in CsI which was selectively pumped by 3889 Å line radiation from a Helium discharge lamp. Jacobs, et al.[3] measured optical amplification of about 4% at 3.2 μ in CsI using such direct optical pumping, and subsequently Rabinowitz, et al.[4] constructed a CsI laser oscillator at 7.19 μ. Following these pioneering achievements at infrared wavelengths, the concept of selective optical pumping of population inversions using line radiation has not been extended to visible wavelengths because of the lack of suitable line coincidences and the relative ease and flexibility of other pumping mechanisms such as direct collisional excitation or excitation-transfer. In the course of the development of short wavelength laser media, the old concept of selective optical pumping using line radiation reemerged in 1975, when Vinogradov, Sobelman, and Yukov[5] and Norton and Peacock[6] proposed the use of x-ray line radiation in one ion species to pump inversions at soft x-ray wavelengths in another ion species. Matthews, et al.[7] have identified several other optically pumped soft x-ray laser schemes and are exploring some of these schemes experimentally. Trebes and Krishnan[8,9] demonstrated UV fluorescence due to optical pumping and excitation in CII ions in a vacuum arc discharge, using AℓIII line radiation from a laser produced plasma. In a companion paper in these proceedings,[10] the collisional-radiative kinetics in the pumped CII ions are described

Published in: Laser Techniques in the Extreme Ultraviolet (OSA, Boulder, Colorado, 1984), S.E. Harris and T.B. Lucatorto, Eds. (AIP, New York, 1984), p. 514.

in detail and the feasibility of lasing at UV wavelengths is discussed.

This paper examines design criteria for a proposed new class of optically pumped, quasi-cw, UV and XUV lasers in six ions of the Be isoelectronic sequence. The possible wavelengths range from 2177 Å to 230 Å in CIII, NIV, FVI, NeVII, NaVIII, and MgIX. In 1964, McFarlane[11] reported laser oscillation on the 3p-3s transitions in CIII at 4647.45 and 4650.16 Å, and in NIV at 3478.67 and 4097.32 Å. Elton[12] discussed the feasibility of extending these 3p-3s ion lasers into vacuum ultraviolet wavelengths. The 3p-3s transitions were chosen both because of the favorable lifetime ratio of these levels and because strong collisional excitation of the 3p upper level is possible from the 2s ground state of the Be-like ions. An important feature of ions of the Be isoelectronic sequence is that in addition to the 3p-3s transitions, the 4p-3d and 4f-3d transitions also have favorable lifetime ratios[13] for sustaining cw laser oscillation. Selective population of the 4p and 4f states could thus lead to a new class of XUV and soft x-ray lasers not considered earlier. This paper describes how intense, line radiation from an ion species in one plasma may be used to resonantly pump Be-like ions in an adjacent plasma from the $2s^2\ ^1S$ ground state to the $2s4p\ ^1P^0$ upper state. Lasing is then possible on the $4p\ ^1P^0$ -- $3d\ ^1D$ transition, with the 3d lower level decaying rapidly to the 3p and 2p levels. Figure 1 shows the relevant energy levels in CIII. At appropriate electron densities and temperatures in the Be-like plasmas, collisions rapidly transfer the $4p\ ^1P^0$ excitation to the $4p\ ^3P^0$ and the 4d and 4f levels. Lasing is therefore also possible on the $4p\ ^3P^0$ -- $3d\ ^3D$ and 4f-3d (singlet and triplet) transitions, as shown in Fig. 1.

PUMP CANDIDATES FOR Be-LIKE IONS

The first requirement of an optically pumped laser is the availability of a line in some ion species which is nearly coincident in wavelength with the absorption transition in the pumped species. Such a pump line should be intense so that the stimulated absorption excites a large fraction of the ground state population to the upper laser level. To achieve this, it is desirable that the pump plasma medium be optically thick at the pump line wavelength. When the upper level of the pump transition is in LTE with the ground state, the pump plasma radiates like a blackbody at this wavelength. In essence, one can create a population ratio of excited state to ground state in the pumped plasma which is characterized by the temperature of the pumping plasma rather than the temperature of the pumped plasma. If the temperature of the pumped plasma is much lower than that of the pumping plasma, strong inversions may be produced. This feature combined with selectivity are advantages of optical pumping over three-body recombination pumping or collisional pumping in which many levels

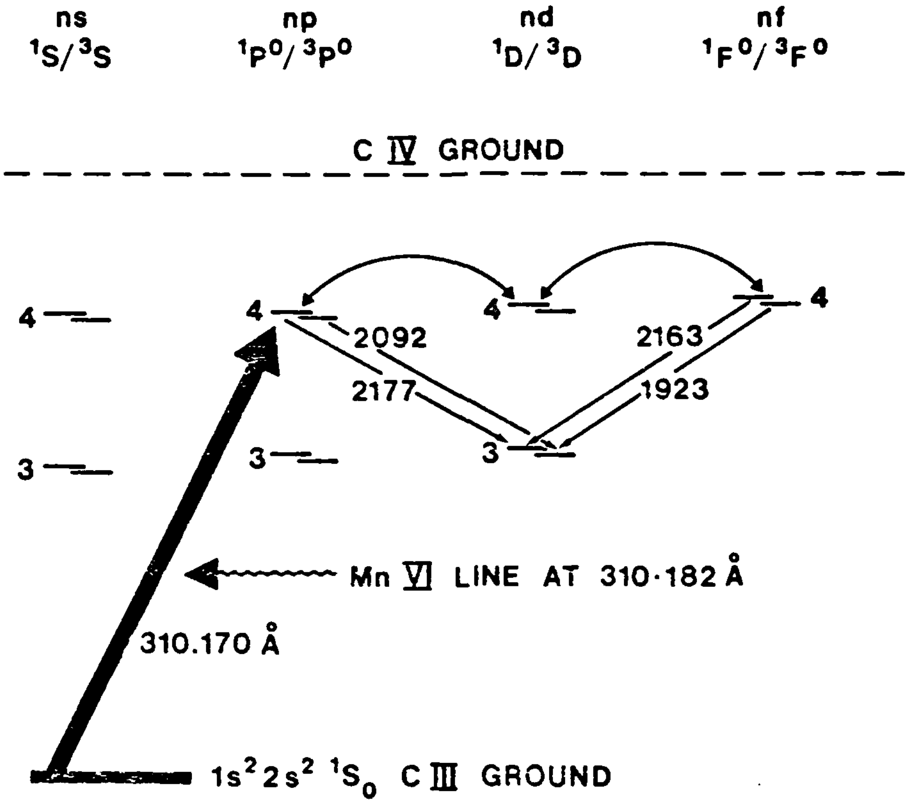


Fig. 1. Energy levels in CIII. Optical pumping of the $2s^2\ ^1S$ -- $2s4p\ ^1P^0$ transition is accompanied by collisional transfer to the $4p\ ^3P^0$, 4d and 4f levels. Quasi-cw lasing is possible on the 4p-3d and 4f-3d transitions.

are pumped. In He-like and Be-like ions in particular, electron collisional pumping with a thermal distribution will tend to populate the 3p levels as well as the 4p levels. Collisional transfer from 3p to 3d can then destroy the inversions.

Table I lists selected optical pumps for ions of the Be-like isoelectronic sequence. OV is omitted because a suitable pump was not found. In each pump ion the pump transition is optically allowed and terminates on one of the ground state configurations.[14] This allows for the creation of an optically thick and intense pump line. Table I also lists selected laser wavelengths from 4p-3d and 4f-3d transitions. Laser wavelengths from the UV to the XUV region are possible with these schemes. He-like ions[7] extend the concept to soft x-ray wavelengths.

Optical pumping with line radiation is best achieved by using two distinct plasmas, with only line radiation at a selected fre-

TABLE I: Optical pumps for the $2s^2\ ^1S$ -- $2s4p\ ^1P^0$ transition in Be-like ions, and typical wavelengths of possible laser transitions, 4p-3d and 4f-3d.

LASER SPECIES	$2s^2$ -- 2s4p WAVELENGTH (Å)	PUMP ION	4p-3d LASER WAVELENGTH (Å)	4f-3d LASER WAVELENGTH (Å)
CIII	310.17	MnVI	2177	2163
NIV	197.23	PIX	1284	1079
FVI	99.203	AℓV	554	513
NeVII	75.765	AℓVIII	404	360
NaVIII	59.759	AℓIX	308	285*
MgIX	48.34	AℓXI	250*	230*

*scaled hydrogenically

quency propagating from the pump plasma into the pumped, lasing medium. In practice, the proximity of the two plasmas results in collisional and other interactions as well, which can spoil the selectivity of the optical pumping and destroy the inversion. To minimize these extraneous interactions, an experimental arrangement is proposed which consists of two coaxial discharges imbedded in a strong axial magnetic field, as shown in Fig. 2. The lasing medium is produced by an arc discharge between hollow electrodes, with N, F, and Ne introduced as gases through one electrode. C, Na, and Mg plasmas may be produced by vacuum arc discharges from electrodes composed of these species. The outer, pump plasma may be generated by an exploding wire array or by a vacuum arc between electrodes composed of the pump element. As shown in Fig. 2, an insulating barrier is interposed between the plasmas to prevent radial breakdown between the electrodes. Furthermore, the strong axial magnetic field acts to confine the plasmas and minimizes radial interactions between them. The use of two separate electrical networks to generate the two plasmas allows independent control over the plasma parameters. In general, the two plasmas require distinctly different densities and temperatures.

The pump ion density and temperature must be high enough to render the pump plasma optically thick to the pump line, in order to maximize its intensity. The high temperature is also necessary

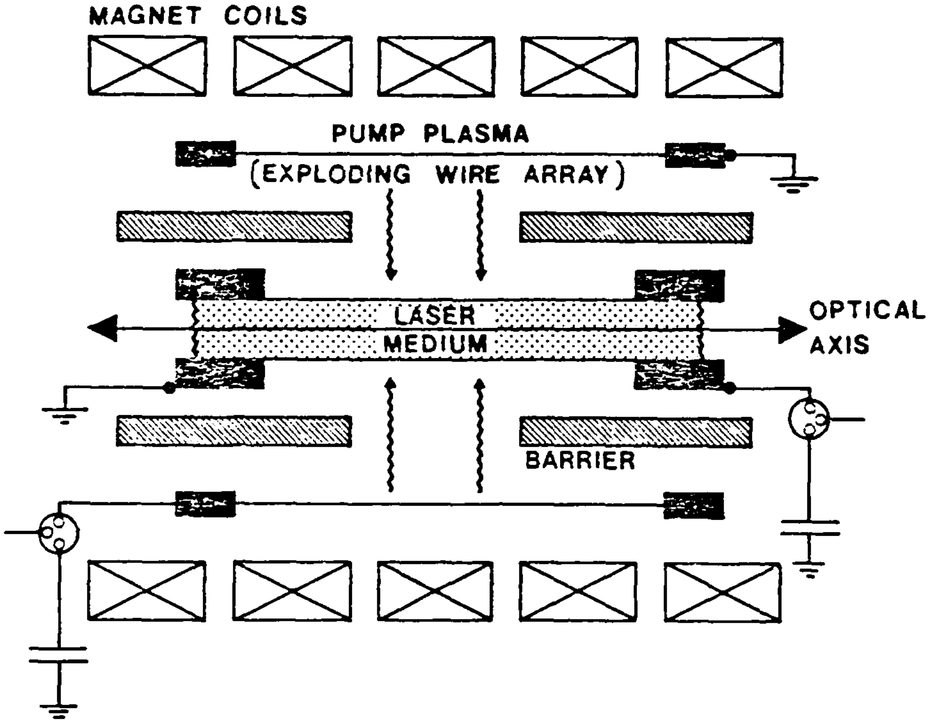


Fig. 2. Schematic diagram of proposed coaxial discharge arrangement.

to overcome the wavelength mismatch between the pump and absorption wavelengths by Doppler broadening. For the pumped plasma, since the ground state of the pumped ion is the primary source of the population inversion, the ion (and hence electron) density should be as high as possible to maximize gain but low enough to avoid optical trapping of the lower laser level and collisional depletion of the upper laser levels. Such depletion can occur by excitation, ionization, and by super-elastic de-excitation. The temperature of the pumped plasma must be low enough to minimize collisional depletion of the inversion, while maintaining the desired ground state density of the laser ions. In general, these disparate requirements are best met by creating two separate plasmas. Laser produced plasmas are also suited to these optical pumping schemes, since they enable the production of plasmas with a wide range of densities and temperatures, corresponding to different laser wavelengths and pulse durations. Two separate lasers are ideal. If a single laser beam is used to produce both plasmas, careful target design is required to satisfy the disparate requirements. Figure 3 shows one suggested experimental configuration for laser produced plasmas. The incident laser beams are focused to two separate line foci by two cylindrical lenses

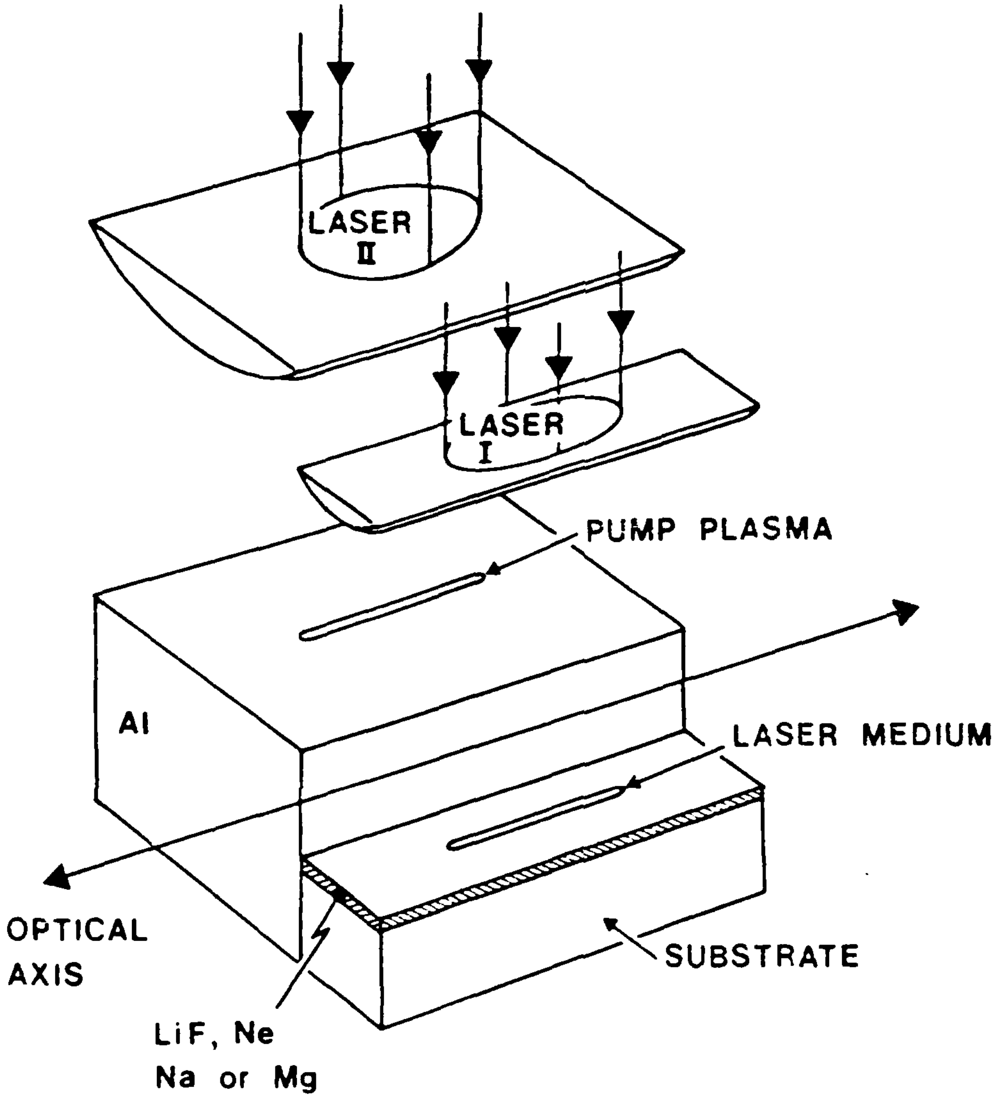


Fig. 3. Proposed experimental configuration for laser produced plasmas. Two different laser may be used, with wavelengths and focal geometries chosen to produce optimal conditions in the two distinct plasmas. Or, a single laser may be split and the two beams delayed with respect to each other to produce the required plasmas.

as shown. One line focus is on Aℓ, to produce surface plasmas of AℓV, AℓVIII, AℓIX, or AℓXI. The other line focus produces the laser medium, FVI, NeVII, NaVIII, or MgIX. For FVI, a lithium fluoride target is convenient. For NeVII, a film of Ne may be frozen onto a substrate as shown by Dixon and Elton.[15] The important feature of the design suggested in Fig. 3 is the step in the composite target. Laser I is first fired onto the lower step to produce the plasma which is the potential lasing medium. This laser produced plasma expands rapidly from the target surface and recombines in a non-equilibrium manner,[16] such that the resultant charge state distribution is characterized by a temperature much higher than the local electron temperature. When this expanding plasma arrives at the plane of the Aℓ surface, it is possible to have a significant population of the pumped ions while at the same time the electron temperature is low. Laser II is delayed with respect to Laser I by the time that it takes the pumped plasma to reach the Aℓ surface plane. A single laser beam may be split into two beams, with one beam delayed with respect to the other. The depth of the step in the target and the delay then provide two independent parameters with which to achieve optimal plasma conditions for optical pumping. The Aℓ surface plasma is dense and hot, so as to maximize the intensity of the pump line. Optical pumping is detected along the optical axis as shown in the figure. A symmetric arrangement is also possible in which two line foci are used on either side of the pumped medium in order to improve the pumping efficiency. The specific requirements of the two distinct plasmas required are now addressed in some detail.

PUMP PLASMA REQUIREMENTS

One requirement of the pump plasma is that the fractional wavelength mismatch, $\Delta\lambda/\lambda_p$, where $\Delta\lambda$ is the difference between the pump line wavelength λ_p and the $2s^2$ -- $2s4p$ absorption wavelength, be less than the fractional Doppler width of the pump line $\Delta\lambda_D/\lambda_p$. This is so as to avoid recourse to relative streaming motion of the two plasmas or very high opacities[6] in order to overcome greater mismatches.

To estimate the pump ion temperature a modified coronal equilibrium calculation was carried out for each pump species, at an electron density determined by the requirement that the pump plasma be opaque (optical depth = 2) at the pump wavelength. Higher densities lead to higher opacities, for which only the outer regions of the pump plasma contribute to the pump radiation field. The coronal model includes for each ion species: collisional ionization, three-body recombination and radiative recombination. For carbon, di-electronic recombination was also included and was found to influence the results. For the other ions, the electron densities are sufficiently high that collisional modification of the di-electronic rates is significant, and accurate rates are not available. Comparison of results without inclusion of di-electronic recombination with similar calculations which include this process[17] revealed little difference over the range of densities and temperatures considered. A typical charge state distribution in an Aℓ plasma is shown in Fig. 4, for an electron density of

1×10^{18} cm^{-3}. Consider, for example, the AℓIX charge state, to be used as a pump for NaVIII. Figure 4 shows that this charge state is dominant at temperatures between 65 eV and 85 eV. Because the distribution is double valued, there are two temperatures at which the opacity is the same. The higher of the two temperatures is preferable because it maximizes the pump line intensity. Thus for this case the incident laser pulse width and focal power density should be adjusted to produce a surface plasma consisting mostly of AℓIX at a temperature of 85 eV. Temperatures were similarly determined for the other pump ions and are listed in Table II. Also shown in the Table are the quantities $\Delta\lambda/\lambda_p$ and $\Delta\lambda_D/\lambda_p$, defined above. For each candidate pair except NeVII - AℓVIII, the Doppler width of the pump line is greater than the mismatch, allowing for good optical coupling. In AℓVIII, the mismatch is about 1.5 Doppler widths. Increasing the opacity of the Aℓ plasma would broaden the line further and overcome the mismatch. A second requirement of the pump plasma is that the pump line intensity must be high enough so that the characteristic time for optical pumping by stimulated absorption be shorter than the radiative lifetime of the 4p level. Then a large fraction of the ground state population is optically pumped to the upper laser levels.

TABLE II: The fractional wavelength mismatch between the pump line and the $2s^2$ — 2s4p line in the lasing ion is compared with the fractional Doppler half width of the pump line. The pump ion temperature is determined by a coronal equilibrium calculation.

LASER SPECIES	PUMP ION	FRACTIONAL WAVELENGTH MISMATCH, $\Delta\lambda/\lambda_p$ (x 10^{-5})	PUMP ION TEMPERATURE (eV)	FRACTIONAL DOPPLER WIDTH $\Delta\lambda_D/\lambda_p$ (x 10^{-5})
CIII	MnVI	4	25	4.6
NIV	PIX	10	90	13
FVI	AℓV	3	22	7
NeVII	AℓVIII	17	70	12
NaVIII	AℓIX	3	85	14
MgIX	AℓXI	5	130	16

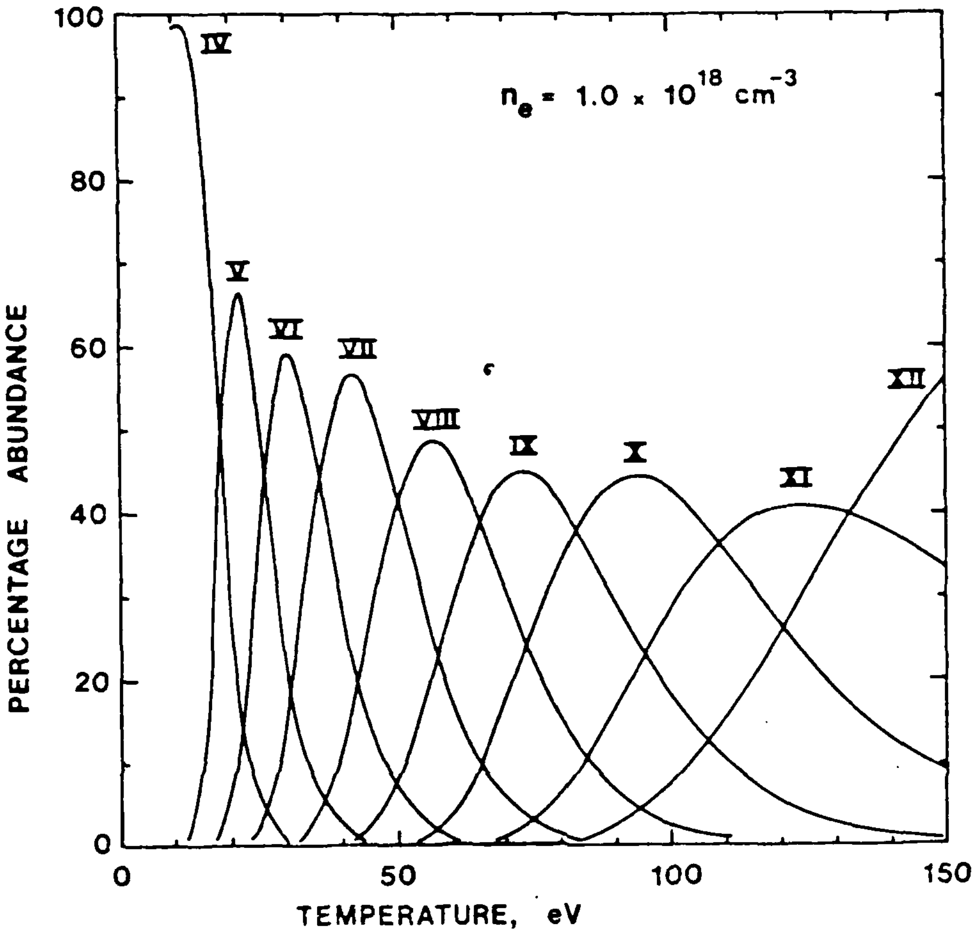


Fig. 4. Charge state distribution in an Aluminum plasma, obtained from a modified coronal equilibrium model. The electron density is 10^{18} cm^{-3}.

To show this, consider the rate equation for the optically pumped upper level, viz.:

$$\frac{dn_u}{dt} = \left(n_\ell - \frac{g_\ell}{g_u} n_u\right) B_{\ell u} I - n_u A_{u\ell} \tag{1}$$

where n_u, n_ℓ, g_u, and g_ℓ are the densities and statistical weights of the upper and lower levels, respectively, I is the pump line intensity integrated over the line profile and over solid angle, and B and A are the Einstein coefficients. Equation (1) is written assuming that the upper level lifetime is determined predominantly by radiative decay to ground. In steady-state:

$$\frac{n_u}{n_\ell} = \frac{B_{\ell u}\ I}{A_{u\ell} + \frac{g_\ell}{g_u} B_{\ell u}\ I} \tag{2}$$

For blackbody line intensity, $I = \frac{8\pi h\nu^3}{c^2}\left(e^{\frac{h\nu}{kT}} - 1\right)^{-1}$,
and Eq. (2) reduces as shown by Apruzese, et al.[17] to:

$$\frac{n_u}{n_\ell} = \frac{g_u}{g_\ell}\ e^{-\frac{h\nu}{kT}} \tag{3}$$

where ν and T are the pump line frequency and blackbody temperature, respectively. Equation (3) shows that when $h\nu/kT \ll 1$, the populations approach the ratio of their respective statistical weights. Such a strong pump condition is not satisfied by all of the pump lines chosen, but significant optical pumping is still possible. For example, in MnVI, the coronal estimate of T = 25 eV and $h\nu$ = 40 eV. For these conditions, if the pump line is absorbed over 4π steradians, $n_u/n_\ell = 0.6$ in CIII. Similarly, in the AℓXI plasma, T = 130 eV and $h\nu$ = 256 eV. Now $n_u/n_\ell = 0.4$ in MgIX. While these ratios are less than the maximum possible ratio of 3 for the 2s-4p absorption transition, they are still quite sufficient to produce high gain lasers, as discussed further below. In summary, Table II shows that at temperatures typical of the pump plasmas, the wavelength mismatch is readily overcome and the pump line intensity is sufficient to pump a large fraction of the ground state population to the 2s4p upper state.

REQUIREMENTS OF THE PUMPED MEDIUM

Turning now to the pumped medium, for each of the laser ions, the temperature T_e was first determined from the coronal equilibrium. Figure 5 shows a charge state distribution in a sodium plasma at a density of 1×10^{17} cm^{-3}. The NaVIII ions are found to be abundant between 45 and 65 eV. In this case, the lower of these two temperatures is chosen so as to minimize deleterious electron collisional effects on the optical pumping. The temperatures appropriate to the other laser ions were similarly determined. These values of T_e are listed in column two of Table III. An upper bound on the electron density was determined by considering four processes which could destroy the inversion: optical trapping of the 3d-2p line, collisional ionization from the pumped levels, collisional de-excitation from the upper laser level, and collisional excitation of the 3p level from the ground state followed by transfer to the 3d level. The most deleterious process was optical trapping, for which the electron density n_e was determined by requiring that optical trapping not increase the 3d lifetime to more than the 4f lifetime. This preserves the possi-

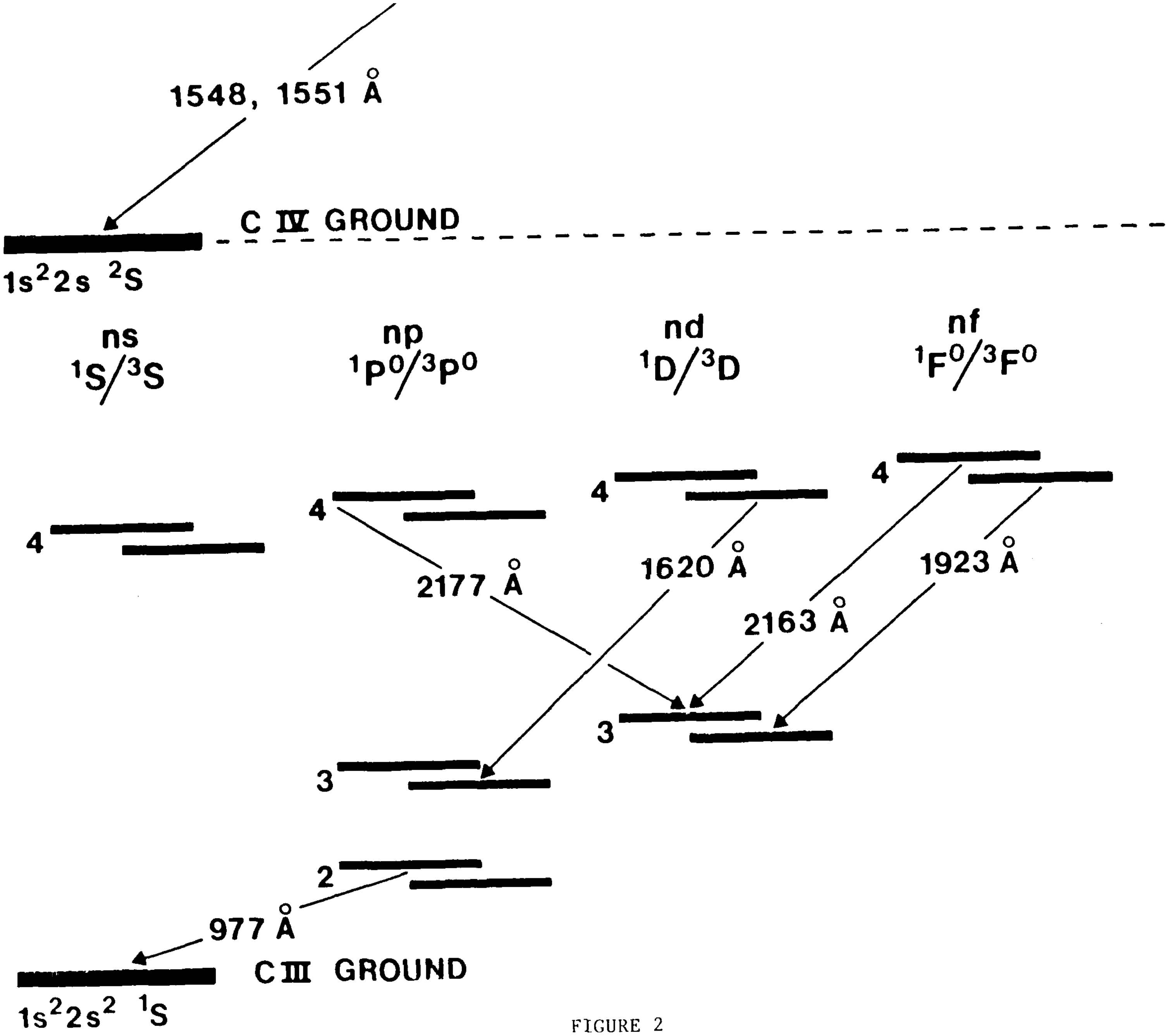

1548, 1551 Å
C IV GROUND
1s²2s ²S
ns
¹S/³S
np
¹P⁰/³P⁰
nd
¹D/³D
nf
¹F⁰/³F⁰
4
4
4
4
2177 Å
1620 Å
1923 Å
2163 Å
3
3
2
977 Å
C III GROUND
1s²2s² ¹S

FIGURE 2

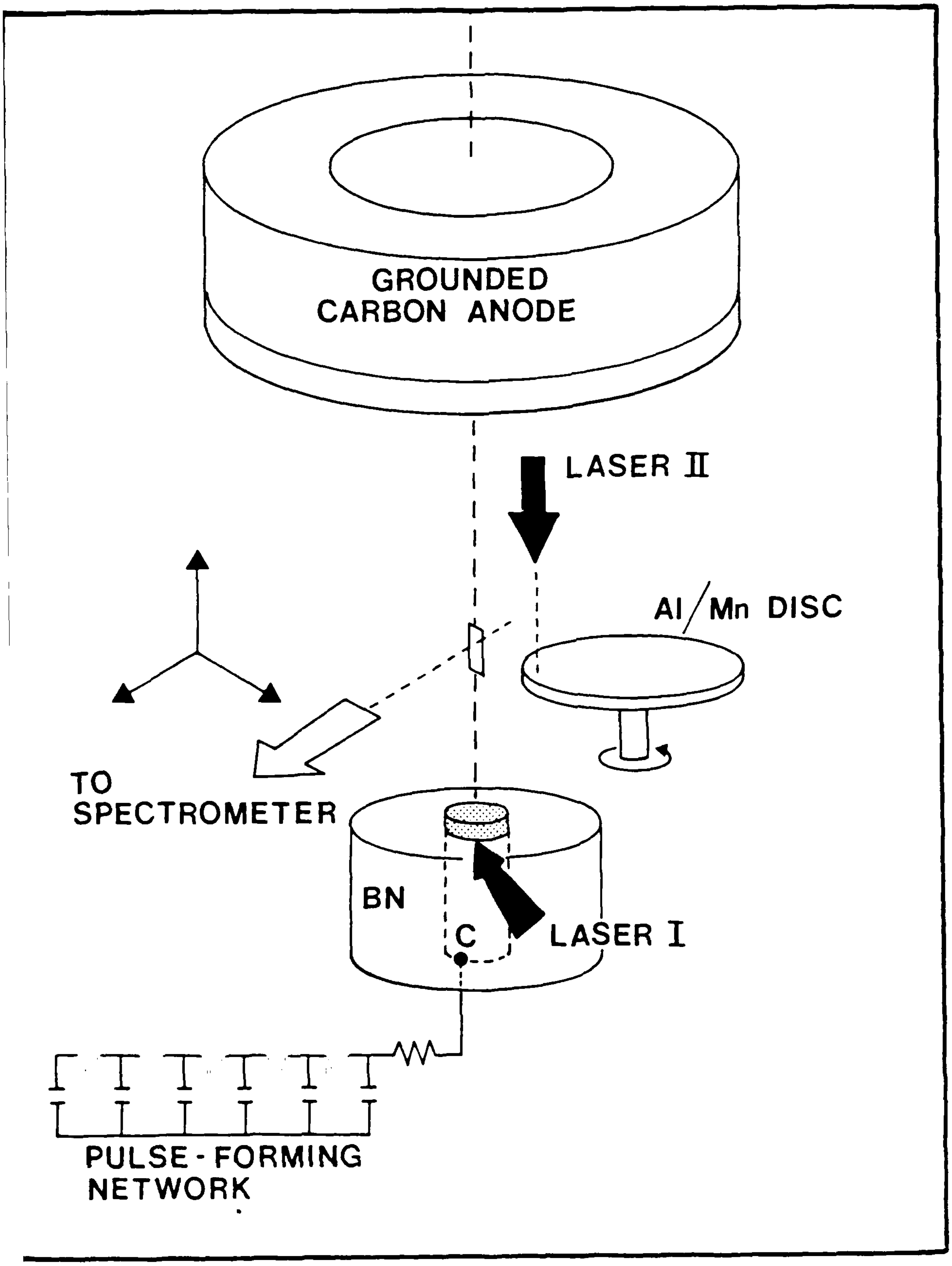

GROUNDED
CARBON ANODE
LASER II
Al/Mn DISC
TO
SPECTROMETER
BN
C
LASER I
PULSE-FORMING
NETWORK

FIGURE 1

FIGURE CAPTIONS

Figure 1.	Schematic diagram of the experimental apparatus.
Figure 2.	Energy levels in CIII and CIV. Optical pumping of the $2s^2\ ^1S$ - $2s4p\ ^1P^0$ transition is accompanied by collisional transfer to the $4p\ ^3P^0$, 4d, and 4f levels. Quasi-cw lasing is possible on the 4p-3d and 4f-3d transitions.
Figure 3.	Observed fluorescence at 2177 Å in CIII.
Figure 4.	Observed fluorescence at 1923 Å in CIII.

REFERENCES

1. P. Rabinowitz, S. Jacobs, and G. Gould, Appl. Opt. **1**, 513 (1962).
2. N. Djeu and R. Burnham, Appl. Phys. Lett. **25**, 350 (1974).
3. M. Krishnan and J. Trebes, Appl. Phys. Lett. 45, 189 (1984).
4. D.L. Matthews, P. Hagelstein, E.M. Campbell, A. Toor, R.L. Kauffman, L. Koppel, W. Halsey, D. Phillion, and R. Price, IEEE J. Quant. Elect. **QE-19**, 1786 (1983).
5. P. Hagelstein, UCRL Report No. 53100, 1981 (unpublished).
6. J. Apruzese, J. Davis, and K.G. Whitney, J. Phys. B: Atom. Molec. Phys. **11**, 20 (1978).
7. M. Krishnan and J. Trebes, in: **Laser Techniques in the Extreme Ultraviolet (OSA, Boulder, Colorado, 1984)**, S.E. Harris and T.B. Lucatorto, Eds. (AIP, New York, 1984), p. 514.
8. J. Trebes and M. Krishnan, in: **Laser Techniques in the Extreme Ultraviolet (OSA, Coulder, Colorado, 1984)**, S.E. Harris and T.B. Lucatorto, Eds. (AIP, New York, 1984), p. 387.

ionization. A rough estimate of the photo-ionization rate is given by assuming that the Mn plasma radiates as a blackbody. For the photo-ionization rate to be comparable with the collisional rates within the n=4 shell, the blackbody temperature required is about 20 eV. Since the Mn plasma in the initial expansion phase has such a temperature or higher, photo-ionization of the 4p level is possible. To test this notion, the spectrometer was tuned to the CIV, 2p $^2P^0$ - 2s ^2S resonance line at 1551 Å. The upper state of this line is coupled to the CIV ground state by a strong dipole transition, and should therefore reveal an increase in the CIV ground state population. Under conditions identical to those described earlier, the ratio of enhanced fluorescence/spontaneous emission measured at 1551 Å was about 12:1. Such an increase could also be due to step-wise collisional excitation from the 4p level. Further research is needed to clarify this deleterious process. One possible way to alleviate photo-ionization is by creating the Mn plasma in a vacuum spark discharge rather than by a CO_2 laser. The vacuum spark discharge may be tailored to produce a plasma consisting predominantly of MnVI ions, at a density high enough to generate an intense, 310 Å pump line, but low enough to minimize broadband radiation. With the laser produced Mn plasma as a pump, we have already observed up to 150:1 enhancements in fluorescence at 2177 Å. Experiments are underway to optimize this fluorescence and to construct an oscillator at both this and the 4f-3d wavelengths.

This research was supported by the Air Force Office of Scientific Research, Grant # 81-0077.

n=4 levels. The 4d-3p and 4f-3d lines were therefore examined for enhanced fluorescence. At the 4d ^{1}D - 3p ^{1}P^0 wavelength of 1620 Å, for a discharge current of 5.6 kA, the ratio of enhanced fluorescence to spontaneous emission observed was 30:1. The enhancement ratio decreased further, to 10:1 and 15:1 at the 4f-3d wavelengths of 2163 and 1923 Å, respectively. Figure 4 shows typical data at 1923 Å, corresponding to the 4f ^{3}F^0 - 3d ^{3}D line. Figure 4(a) shows the enhanced fluorescence when the Mn plasma was created 43 μs after intiation of the 5.6 kA C discharge. After subtraction of the spurious background (not shown), the enhancement ratio is about 15:1. Figure 4(b) shows the fluorescence when the discharge current was reduced to 3.3 kA. At this lower current, although the fluorescence remains the same, the spontaneous emission has decreased significantly, thus increasing the enhancement ratio.

For fixed pump plasma and discharge conditions, the fluorescence enhancement ratio decreases from about 150:1 at 2177 Å to 30:1 at 1620 Å and 15:1 at 2163 and 1923 Å. Earlier analysis [7] had shown that the n=4 levels in CIII should be driven into statistical equilibrium on the time scale for radiative decay from 4p. Also, the times for single-step collisional ionization from the n=4 levels were found to be much longer than the radiative lifetimes. When the n=4 levels are in statistical equilibrium, the ratios of the 4s, 4p, 4d, and 4f level populations should be 0.0625:0.1875:0.3625:0.4375. Hence most of the pumped 4p population should reside in 4d and 4f and the enhancement ratios for these levels should be as high as that for the 4p level, contrary to the experimental observations. There are two possible causes for this discrepancy: firstly, the C plasma density and the collisional rate coefficients may be lower than estimated, and secondly, the 4p level may be depopulated by multi-step collisional ionization or by photoabove the baseline. To determine what fraction of the observed fluorescence at 2177 Å might be due to line or continuum radiation from the Mn plasma which enters the field of view of the spectrometer, the C discharge was turned off and only the Mn plasma was produced. Figure 3(d) shows that under these conditions, there is indeed some spurious background detected at 2177 Å, but this is much less than the observed fluorescence from the CIII ions. After subtracting this background from the total signal [Fig. 3(c)] and taking the scale factor into account, the ratio of fluorescence/spontaneous emission at 2177 Å is between 100:1 and 150:1. Figure 3(c) actually shows data from three consecutive shots superimposed, and reveals the good reproducibility of the fluorescence. Figure 3(e) shows the enhanced fluorescence with better temporal resolution. The fluorescence is observed to persist for about 1.8 μs after the Mn plasma is produced. The radiative lifetime of 4p is 5 ns. Thus if the 4p level is inverted with respect to the 3d level, a quasi-cw laser at 2177 Å is possible. It might be argued that the observed fluorescence is due to collisional excitation of the 4p level in CIII by hot electrons from the laser produced Mn plasma which expand into the C discharge. If this were the case, then a laser produced Al plasma should also produce enhanced fluorescence. When an Al pump plasma was produced at the same location as the Mn plasma, no enhanced fluorescence was observed. In addition to this test, the CII, $2s^2\ 2p\ ^2P^0$ - $2s2p^2\ ^2D$ line at 1335 Å was also examined. Neither the Mn nor the Al plasma produced enhanced fluorescence at this wavelength, confirming that the fluorescence observed at 2177 Å was indeed due to selective photo-excitation by MnVI line radiation.

At the densities and temperatures typical of the carbon arc, it has been shown [7] that electron and ion collisions rapidly transfer the pumped 4p population to the other focusing Laser I onto the cathode. At a distance of 15 mm downstream from the cathode, the electron density and temperature are 10^{15} cm^{-3} and 3 eV [8], respectively. About 40 μs after discharge initiation, the pump plasma is produced by focusing Laser II onto a Mn target on a rotatable disc as shown in Fig. 1. The focal spot of the laser is 7 mm off axis from a point 15 mm downstream from the cathode. Spontaneous emission and enhanced fluorescence in CIII were measured by a vacuum ultraviolet spectrometer which imaged a 0.1 x 2 mm region on the discharge axis at the 15 mm downstream location.

A partial energy level diagram of CIII and CIV is shown in Fig. 2. The 2s ^1S - 4p $^1P^0$ transition at 310.17 Å is resonantly pumped by 310.182 Å line radiation from MnVI ions in the laser produced plasma. The Doppler width of the MnVI line at a temperature of 30 eV is 17 mÅ, which is greater than the 12 mÅ wavelength mismatch. Photo-excitation of CIII by MnVI was therefore expected, with enhanced fluorescence on the 4p $^1P^0$ - 3d ^1D line at 2177 Å. At $n_e \sim 10^{15}$ cm^{-3} and $T_e \sim 3$ eV in the C plasma, electron and ion collisions will rapidly transfer the 4p population to the 4s, 4d, and 4f levels [7]. Enhanced fluorescence was therefore also expected from these levels. Typical results obtained at 2177 Å are shown in Fig. 3.

Figure 3(a) shows the C discharge current vs time. Figure 3(b) shows the spontaneous emission at 2177 Å, in the absence of the Mn pump plasma. When the Mn plasma was produced 43 μs after discharge initiation, the resultant enhanced fluorescence at 2177 Å is shown in Fig. 3(c). To capture this trace on film, the gain of the photomultiplier detector was kept identical to that for Fig. 3(b), but the sensitivity of the recording was reduced by a factor of 20. Hence the spontaneous emission is not visible

In 1961, Rabinowitz, Jacobs and Gould [1] reported laser oscillation at 7.12 μ in CsI, when the upper laser level was photo-excited by 3880 Å resonance line radiation from a helium lamp. Djeu and Burnham [2] extended this concept of selective photo-excitation to a visible wavelength by pumping a 5461 Å laser in HgI in a vapor cell, using line radiation from HgI in an adjacent cell. Recently, Krishnan and Trebes [3] have proposed a new class of Be-like, photo-excited lasers with wavelengths from 2177 Å in CIII to 213 Å in MgIX. This Letter reports observed fluorescence from the 4p, 4d, and 4f levels in CIII, when the 4p level was pumped by 310 Å line radiation from MnVI. The radiative lifetime ratio of 4p/3d is 40, while that for 4f/3d is 7.5. Both the 4p-3d and the 4f-3d lines are thus candidates for quasi-cw, ultraviolet lasers. Selective photo-excitation with line radiation has also been proposed as a means for pumping soft x-ray lasers in H-like and He-like ions [4,5]. Extensive numerical analyses [5-7] suggest that terawatt lasers and terawatt level pulsed-power technology are capable of providing adequate pump power in line radiation with which single-pass, high gain lasers may be produced at soft x-ray wavelengths. At ultraviolet wavelengths, the pump power required is orders of magnitude lower, and smaller gains are tolerable because of the availability of high reflectance optics. The results presented in this Letter were obtained with a pump laser power of 100 MW. Since CIII is isoelectronic with MgIX, the collisional-radiative kinetics elucidated by this research shed light directly on possible soft x-ray lasers in MgIX.

Figure 1 shows a schematic diagram of the experimental apparatus. The CIII ions are produced in a laser triggered vacuum arc discharge between a 6 mm diameter carbon cathode and a hollow carbon anode 100 mm downstream. The discharge, from a pulse-forming network, with typically 5 kA current and 60 μs pulse duration, is triggered by

To be published in
Appl. Phys. Lett.
(March 1, 1985).

APPENDIX IV

OBSERVED ENHANCED FLUORESCENCE AT 2177, 2163, 1923, AND 1620 Å IN CIII BY PHOTO-EXCITATION WITH MnVI LINE RADIATION AT 310 Å

Niansheng Qi, Hayrettin Kilic, and Mahadevan Krishnan
Yale University
Section of Applied Physics
New Haven, Connecticut 06520

Abstract

Line radiation at 310.182 Å from MnVI ions in a laser produced plasma was used to resonantly pump CIII ions in an adjacent, vacuum arc discharge from the 2s ^1S ground level to the 4p $^1P^0$ upper level. Enhanced fluorescence by up to a factor of 150 was measured on the 4p $^1P^0$ - 3d ^1D line at 2177 Å. Collisional exchanges between the n=4 levels transfer the pumped 4p population to the 4d and 4f levels. Enhanced fluorescence was also measured on the 4d ^1D - 3p $^1P^0$ line at 1620 Å and on the 4f-3d lines at 2163 Å and 1923 Å respectively.

3. S. Jacobs, G. Gould, and P. Rabinowitz, Phys. Rev. Lett. 7, 451 (1961).
4. P. Rabinowitz, S. Jacobs, and G. Gould, Appl. Opt. 1, 513 (1962).
5. A.V. Vinogradov, I.I. Sobelman, and E.A. Yukov, Sov. J. Quant. Electron. 5, 59 (1975).
6. B.A. Norton and N.J. Peacock, J. Phys. B 8, 6 (1975).
7. D.L. Matthews, P. Hagelstein, E.M. Campbell, A. Toor, R.L. Kauffman, L. Koppel, W. Halsey, D. Phillion, and R. Price, IEEE J. Quant. Elect. QE-19, 1786 (1983).
8. J. Trebes and M. Krishnan, Phys. Rev. Lett. 50, 679 (1983).
9. J. Trebes and M. Krishnan, IEEE J. Quant. Elect. QE-19, 1870 (1983).
10. J. Trebes and M. Krishnan, these proceedings.
11. R.A. McFarlane, Appl. Phys. Lett. 5, 91 (1964).
12. R.C. Elton, Appl. Opt. 14, 97 (1975).
13. M. Duguay, Laser Focus 9, 45 (1983).
14. R.L. Kelly and L.J. Palumbo, NRL Rept. 7599 (1973).
15. R.H. Dixon and R.C. Elton, J. Opt. Soc. Am.-B 1, April 1984.
16. Y.B. Zeldovich and Y.B. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena, Vol. 2 (Academic Press, New York, 1967), p. 571.
17. R. Hulse, personal communication.
18. J.P. Apruzese, J. Davis, and K.G. Whitney, J. Appl. Phys. 53, 4020 (1982).
19. T. Holstein, Phys. Rev. 72, 1212 (1947).
20. W.L. Morgan, personal communication.
21. R.J. Dukart, 14th Winter Colloquium on Quantum Electronics, Snowbird, Utah, January 10-13, 1984.

that all these ion species are capable of lasing even with weak optical pumping. For example, the ratio of 4f to $2s^2$ populations in CIII required is 1×10^{-4}. Strong optical pumping would result in a ratio of 0.6. For MgIX, the required ratio is 0.06. Again, the saturated ratio would be 0.4. For the high gain lasers, gain saturation of the lasing transitions would increase the required inversion densities and strong optical pumping to saturation would probably be required.

CONCLUSION

The above analysis has shown that Be-like, optically pumped plasmas offer the potential for high gain, quasi-cw lasers at wavelengths from 2177 Å down to 230 Å. The new class of lasers described here may be tested using laser produced plasmas or by creating coaxial arc discharges. The longer wavelength candidates may be studied at relatively low input powers with long pulse durations. Detailed spectroscopic studies of the optical pumping and subsequent kinetics would reveal key scaling laws that may be directly applicable to the design of the isoelectronically scaled, less accessible shorter wavelength candidates. The design criteria summarized in Table III suggest that in MgIX, an inversion density of 1.5×10^{15} cm^{-3} may be maintained by strong pumping from a ground state population of 3×10^{16} cm^{-3}. If the laser medium is 0.5 cm in diameter and 4 cm long, the quasi-cw output power at 230 Å is $\sim 10^8$ W. The power required for optical pumping is then $\sim 10^9$ W. If only 10% of the total power radiated by the AℓXI pump line is absorbed by MgIX, the total power required in the AℓXI pump line is then $\sim 10^{10}$ W, which for a 10 ns laser pulse, requires 100 J of total energy in the pump line. The 10 ns output duration is 1000 times longer than the radiative lifetimes of the 4f levels. Recently,[21] single soft x-ray lines with energies >100 J have been measured in many elements in terawatt, imploding plasma discharges. Existing pulsed power technology or high power lasers may thus be used to test the XUV laser schemes proposed in this paper.

ACKNOWLEDGMENTS

This research was supported by the Air Force Office of Scientific Research (Grant # 81-0077). Helpful discussions with W.R. Bennett, Jr. and R. Jensen are gratefully acknowledged. We are indebted to W.L. Morgan of Lawrence Livermore Labs. for the atomic data on CIII. After preparation of this manuscript, we were informed by R.C. Elton that one of the schemes proposed here, the MgIX - AℓXI combination, was suggested earlier[15] by J.F. Seely.

REFERENCES

1. W.R. Bennett, Jr., personal communication
2. C. Boeckner, J. Res. Natl. Bur. St. 5, 13 (1930).

TABLE III: Parameters of the optically pumped laser media. T_e is determined by a coronal equilibrium; n_e is given by requiring that optical trapping not increase the 3d lifetime to larger than the 4f lifetime, so that quasi-cw lasing is possible; the time, τ, for collisional transfer from 4p to 4f, and the required inversion density, n_{4f}, for specified gain, α, are also computed.

LASER SPECIES	T_e (eV)	n_e (cm^{-3}) ($\times 10^{15}$)	4p-3d LIFETIME (ns)	4f-3d LIFETIME (ns)	τ (ns)	α (cm^{-1})	n_{4f} (cm^{-3}) ($\times 10^{13}$)
CIII	4	1	11	1	1	0.01	0.004
NIV	7	4	4	0.25	0.5	0.01	0.01
FVI	20	70	0.7	0.06	0.07	1	4
NeVII	30	100	0.4	0.03	0.07	10	70
NaVIII	45	200	0.2	0.02	0.04	10	100
MgIX	55	200	0.15	0.01	0.03	10	150

For the rest of the ions, the oscillator strengths were assumed to be equal to those in CIII and the lifetimes were scaled hydrogenically.

For the chosen values of n_e and T_e, the times τ for collisional transfer from the 4p to 4f levels are listed in column six of Table III. Since these collisional transfer times are up to a factor of ten shorter than the 4p-3d radiative lifetimes and are comparable with the 4f-3d radiative lifetimes, most of the optically pumped 4p population will be transferred to 4f. The dominant lasing transitions will be the 4f-3d transitions. Under these conditions of n_e and T_e, the time for ionization from the 4f levels was estimated to be about a hundred times longer than the 4f-3d radiative lifetime. Finally, the inversion density n_{4f} required to produce a specified gain α on the 4f-3d lines was computed and is also shown in Table III. For CIII and NIV, α of 0.01 cm^{-1} was chosen because reflecting optics can be used. FVI also allows a hole coupled reflecting cavity, but the lower reflectivities available at 500 Å demand α of 1 cm^{-1}. For NeVII, NaVIII, and MgIX, an ASE source is required, with $\alpha > 10$ cm^{-1}. Comparison of the values of n_e and n_{4f} shown in Table III reveals

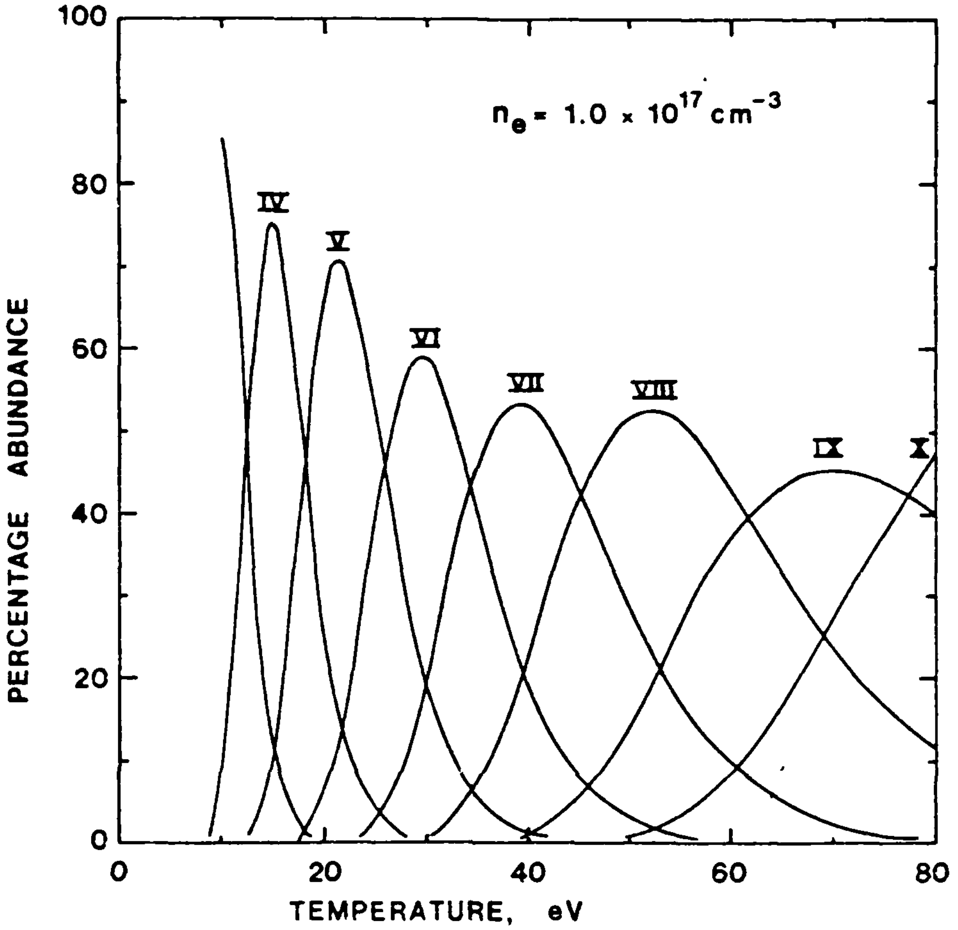


Fig. 5. Charge state distribution in a Sodium plasma, obtained from a modified coronal equilibrium model. The electron density is 10^{17} cm^{-3}.

bility of quasi-cw lasing on the 4f-3d transitions. As a worst case of optical trapping, the 2p $^3P^0$ level was assumed to be in LTE with the ground state, which maximizes its population. For a given density of the 2p $^3P^0$ level, the optical depth of the laser medium at the 3d ^3D -- 2p $^3P^0$ wavelength was computed. Using a Holstein escape factor,[19] the modified lifetime of the 3d ^3D level was then computed. The maximum allowed density of the 2p $^3P^0$ level was that which increased the 3d lifetime to just equal the 4f lifetime. Quasi-neutrality then yielded the upper bound on n_e. The values of n_e so determined are listed in column three of Table III. Also listed are the radiative lifetimes (in ns) of the lasing transitions. The lifetimes, energies, and collisional rate coefficients in CIII were obtained from Morgan.[20]

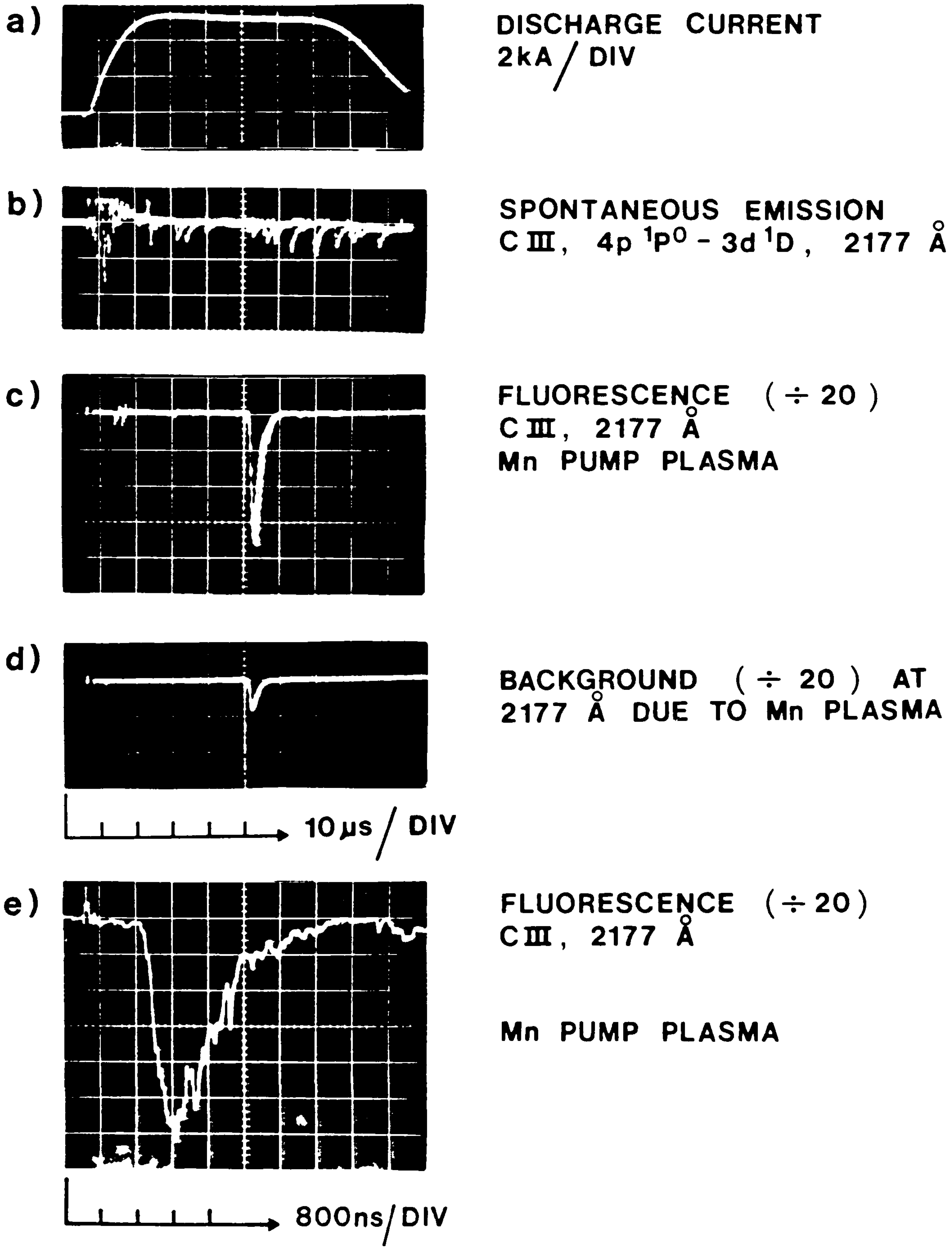
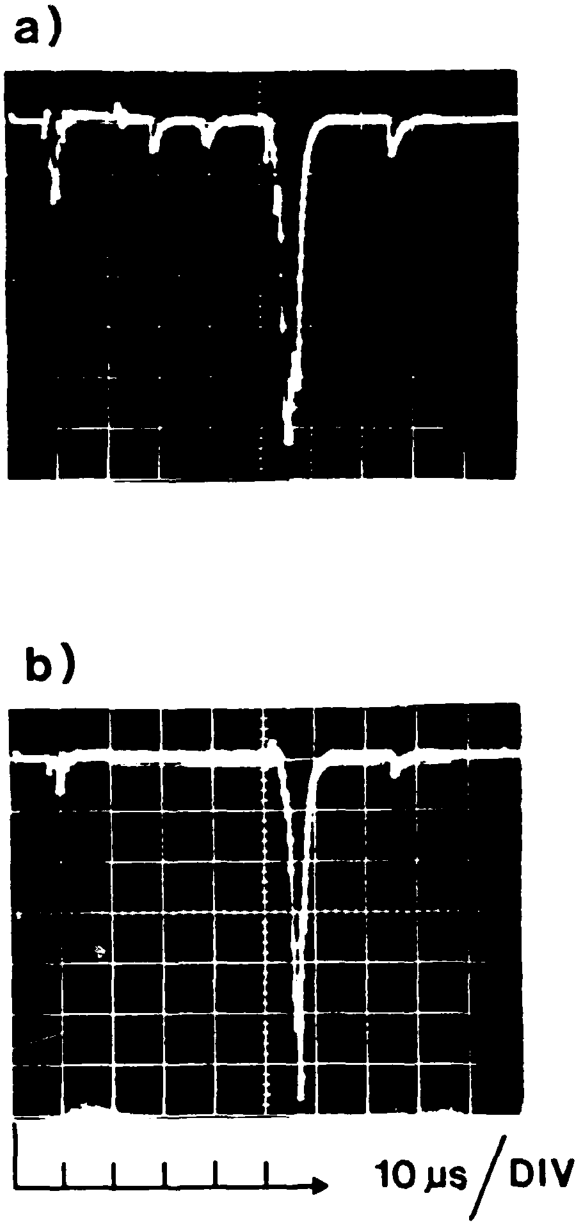

a)
DISCHARGE CURRENT
2kA / DIV
b)
SPONTANEOUS EMISSION
C III, 4p $^1P^0$ - 3d ^1D, 2177 Å
c)
FLUORESCENCE (÷ 20)
C III, 2177 Å
Mn PUMP PLASMA
d)
BACKGROUND (÷ 20) AT
2177 Å DUE TO Mn PLASMA
10 μs / DIV
e)
FLUORESCENCE (÷ 20)
C III, 2177 Å
Mn PUMP PLASMA
800ns / DIV

FIGURE 3



FLUORESCENCE
C III, 4f $^3F^0$ - 3d ^3D, 1923 Å
Mn PUMP PLASMA

5.6kA DISCHARGE

3.3kA DISCHARGE

FIGURE 4

APPENDIX V

Abstract Submitted
for the Annual Meeting of the
Plasma Physics Division of the
American Physical Society
Oct. 29 - Nov. 4, 1984

PACS No.: 42.55

Design Considerations for Optically Pumped, Quasi-cw, UV to Soft X-ray Lasers in Be-like Ions,* M. KRISHNAN and J. TREBES,† Yale U.--We have proposed[1] a new class of quasi-cw, UV to soft x-ray lasers in Be-like CIII, NIV, FVI, MgVII, NaVIII, and MgIX ions which are optically pumped using line radiation from MnVI, PIX, AℓV, AℓVIII, AℓIX, and AℓXI ions. The plasmas required for these schemes may be produced using lasers or pulsed power technology. For both the pump and the pumped plasmas, modified coronal equilibrium calculations provide estimates of the required temperatures. For each laser ion, processes which spoil the optically pumped inversion are considered, such as collisional ionization, deexcitation, collisional population and optical trapping of the lower laser levels. Upper bounds to the electron density n_e result from such considerations. Lower bounds to n_e are given by requiring rapid collisional transfer of the pumped 4p population to the 4f upper laser levels. The required regimes of n_e and T_e are discussed in light of proposed experimental configurations.

*Supported by AFOSR Grant # 81-0077.

†Present address: Lawrence Livermore Lab., Livermore, CA.

[1] M. Krishnan and J. Trebes, Appl. Phys. Lett. 45 (1984).

(X) Prefer Poster Session

M. Krishnan

Mahadevan Krishnan (APS Member)
Yale University
Applied Physics
Mason Lab
P.O. Box 2159 Yale Station
New Haven, CT 06520

Abstract Submitted
for the Annual Meeting of the
Plasma Physics Division of the
American Physical Society
Oct. 29 - Nov. 4, 1984

PACS No.: 42.55

Observation of Enhanced Fluorescence at UV Wavelengths in CIII by Optical Pumping with MnVI Line Radiation,* N. QI, H. KILIC, and M. KRISHNAN, Yale U.—A new class of optically pumped, Be-like lasers capable of lasing from the UV to soft x-ray wavelengths has recently been proposed.[1] This paper reports measurements of enhanced fluorescence in CIII due to optical pumping with MnVI line radiation. The CIII ions are produced in a laser-initiated vacuum-arc. A laser produced Mn plasma is produced adjacent to the carbon discharge axis. MnVI line radiation at 310.17Å resonantly pumps the $2s^2\ {}^1S$—$2s4p\ {}^1P^0$ transition in CIII. Enhanced fluorescence by up to a factor of 150 was observed on the $4p\ {}^1P^0$—$3d\ {}^1D$ transition at 2177Å. Enhanced fluorescence was also observed on the 4d-3p and 4f-3d transitions at wavelengths of 1620, 1923, and 2163Å, respectively. Observation of enhanced fluorescence on the CIV resonance lines at 1548 and 1551Å suggests that the selective optical pumping may be accompanied by broadband photoionization out of the n=4 levels. Prospects for building a quasi-cw, UV laser in CIII are discussed.

*Supported by AFOSR Grant # 81-0077.

[1] M. Krishnan and J. Trebes, Appl. Phys. Lett. 45 (1984).

(X) Prefer Poster Session

M. Krishnan

Signature of APS Member
Mahadevan Krishnan
Yale University
Applied Physics
Mason Lab
P.O. Box 2159 Yale Station
New Haven, CT 06520

Abstract Submitted
for the Annual Meeting of the
Plasma Physics Division of the
American Physical Society
Oct. 29 - Nov. 4, 1984

PACS No.: 42.55

Optical Pumping of CIII Ions in a Magnetically Confined C Plasma Using MnVI Line Radiation from an Adjacent Mn Plasma, H. KILIC, N. QI, and M. KRISHNAN, Yale U.--Significant enhanced fluorescence has been observed in CIII ions in an unconfined vacuum-arc discharge by optical pumping with MnVI line radiation.[1] This paper reports results of optical pumping of a magnetically confined C discharge. Pulsed, uniform magnetic fields with strengths up to 0.8T are produced by two 7 cm diam coils with a 1.5 cm gap, driven by a pulse-forming network. A 0.5 cm diam x 2 cm long C discharge is produced on the magnetic field axis. The laser produced Mn plasma is parallel to the C plasma, at a transverse distance of 0.8 cm. The 1.5 cm gap between the magnet coils enables spectrometers and a Fabry-Perot resonator to view the optically pumped plasma region. Two potential quasi-cw laser transitions are studied using the Fabry-Perot cavity: 4p $^1P^0$--3d ^1D at 2177Å and 4f $^1F^0$--3d ^1D at 2163Å. Prospects for optimizing the gain by coaxial pumping of the CIII ions using a coaxial, pulsed discharge Mn plasma are discussed.

*Supported by AFOSR Grant # 81-0077.

[1] N. Qi, H. Kilic, and M. Krishnan, this conference.

(X) Prefer Poster Session

M. Krishnan

Signature of APS Member
Mahadevan Krishnan
Yale University
Applied Physics
Mason Lab
P.O. Box 2159 Yale Station
New Haven, CT 06520