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POPULATION INVERSION IN LASER-PRODUCED PLASMAS BY PUMPING WITH OPACITY BROADENED LINES

by

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ABSTRACT

It has been noted that line radiation, for example, the first members of the Lyman series of C^{5+}, is optically thick at the surface of a laser-irradiated carbon target. Optical depths of the order of 10^4 can be anticipated with appropriate focusing geometry. Using such an optically thick and broadened line source it is calculated that population inversion and a measurable super-radiant gain can be achieved by resonance pumping in neighbouring ion species.

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1. INTRODUCTION

Population inversion of atomic levels with transition energies in the soft x-ray region has been observed in the freely expanding plasmas produced at the surface of laser-irradiated solid targets, Irons and Peacock (1974a). The inversion is a natural consequence of the fact that the rate of electronic recombination which occurs preferentially into the upper quantum levels, is considerably slower than the volume expansion rate. The highly ionised ion species eg. C^{5+}, which are effectively 'frozen' into a low temperature freely expanding plasma show inversion for those levels, n = 2, 3, 4 etc, which lie below the thermal limit. No inversion takes place relative to the ground level which remains by far the most heavily populated. The low absolute density of the ions in the excited states is a drawback to any use of this simple system as an x-ray laser, Irons and Peacock (1974b).

In this communication it it proposed that the high population density of the ions on the ground level can become involved in the inversion process by resonance pumping from a line source which is so broadened by optical opacity as to overlap the resonance transitions in the ion of interest. For the sake of illustration we consider inversion between the n = 4, 3 and the n = 2 principal quantum levels of C^{4+} ions in an expanding laser-produced plasma. The C^{4+} ions are optically pumped by the Lyman α radiation from a neighbouring, optically thick, laser-produced plasma source. It has been noted in our laser-produced plasma studies, Galanti et al (1974), that the intensity of the Lyman α (C^{5+}) profile shows considerable apparent broadening due to opacity and it is anticipated that with suitable focusing geometry the optical depth may be made to exceed 10^3. Resonance pumping using this "opacity broadened" source is a considerably more efficient means of populating upper levels than by electron collisions as suggested for example by Bristow et al (1972). A brief review of other possible methods of setting up conditions for super-radiance in the soft x-ray region is given by Duguay (1973).

2. THE ENERGY LEVELS INVOLVED IN OPTICAL PUMPING

In order to take advantage of resonance optical pumping the frequency of the upper level above ground in the pumped ion should be as close as possible to the central frequency in the line source, any difference being taken up by opacity broadening of the latter. The possibility of using the Lyman lines of single-electron ion species suggest itself for the pump source with Lyman α normally the broadest line. Resonance transitions in helium-like ions are convenient transitions to be pumped since the target ions have closed electron shell configurations following on from a succession of ion stages of low ionization potential. The helium-like ion is therefore a "stable" ion stage in an ionizing plasma such as is produced by laser irradiation of solid targets. Moreover, only a relatively small amount of energy is required for the helium ion to appear in the ground state.

It can be seen from figure 1, that carbon and nitrogen ions offer the best possibilities in view of the closeness of suitable levels. Since the pumping rate decreases into the higher levels, the absorption coefficient scaling as $A_{1n}\ \lambda_{1n}^2$, the pumped levels should not be much greater than $n \simeq 4$. From figure 1, $n = 4$ in $\underline{\text{CV}}$ and $n = 3$ in $\underline{\text{NVI}}$ are likely upper levels in the pumped ion. In order to produce level inversion say between the 4p and the $n = 2, 3$ levels in $\underline{\text{CV}}$ say, the $1s^2\ {}^1S_0$ - $1s\ 4_p\ {}^1P_1$ CV transition at 33.426 Å should be pumped by the opacity-broadened $1s\ {}^2S$ - $2p\ {}^2Po$ $\underline{\text{CVI}}$ line whose central wavelength is 33.736 Å.

3. THE PUMPED PLASMA

The parameters of density and temperature in the pumped plasma are determined by the requirements that the pumping rate from the ground level into the upper level has to be at least of the same order as the reverse spontaneous decay rate, while collisional excitation to, or de-excitation from the upper level should be relatively insignificant. Considering the populating rates for the n = 4, 3 and 2 levels of $C\overline{\underline{V}}$, we have,

$$\frac{d\ n_4}{dt} = n_1\ P_{14} - n_4 \cdot \sum_{q<4} A_{4q} + n_1 n_2\ x_{14} \qquad \ldots (1)$$

$$\frac{d\ n_3}{dt} = n_4\ A_{43} - n_3 \cdot \sum_{q<3} A_{3q} + n_1 n_2\ x_{13} \qquad \ldots (2)$$

$$\frac{d\ n_2}{dt} = n_4\ A_{42} + n_3\ A_{32} - n_2\ A_{21} = n_1 n_e x_{12}\ , \qquad \ldots (3)$$

we define the pumping rate, P , by

$$P_{14} = \frac{4\ \pi}{C} \cdot \Phi_0 \int B_{14}\ (\nu)\ d\nu\ , \qquad \ldots (4)$$

where B_{14} is the absorption coefficient expressed in units of energy density and Φ_o, assumed constant over the whole width of the $C\underline{V}$ transition, is the flux intensity (watts $ster^{-1}$ unit $frequency^{-1}$) of the pump source.

Initially we make the gross simplification of neglecting all collisional processes but assume that the sub levels are statistically populated. Then from equation (2) in the steady state we have

$$\frac{n_4}{n_3} = \frac{A_{32} + A_{31}}{A_{43}} \qquad \ldots (5)$$

and from equation (2) and (3), neglecting $n_1 n_e\ x_{12}$,

$$\frac{n_4}{n_2} = \frac{A_{21}}{A_{42} + \left(\frac{A_{32}\ A_{42}}{A_{32}+A_{31}}\right)} \qquad \ldots (6)$$

If Φ_0 is the black-body intensity of the pump source at a temperature corresponding to the temperature of the plasma source KT_p (section 4) then

$$n_4 \cdot \sum_{q<4} A_{4q} = n_1 \frac{4\pi}{C} \cdot \Phi_0 \int B_{12}(\nu)\, d\nu = n_1 \frac{g_4}{g_1} A_{41} \frac{1}{(e^{h\nu_{14}/KT_p} - 1)}$$

$$\frac{n_4}{n_1} = \frac{g_4}{g_1} \frac{A_{41}}{(A_{41} + A_{43} + A_{42}).\quad (e^{h\nu_{14}/KT_p} - 1)} \qquad \text{... (7)}$$

Since $h\nu_{14}$ is 368 eV and $KT_p \sim 200$ eV (Galanti and Peacock (1974)), then the upper level is nearly saturated with respect to the ground level of the C$\underline{V}$ ion and $n_4/n_1 \simeq 1/5$. With higher flux intensities on the target surface this ratio can readily be made to approach unity.

From equations (5) and (6) we then have a level population, in level n = 4, in excess of that in the lower, n = 3, 2 levels

$$\frac{n_4\, g_3}{n_3\, g_4} = 37.2 \qquad \text{... (8)}$$

$$\frac{n_4\, g_2}{n_2\, g_4} = 31.5 \qquad \text{... (9)}$$

We have examined the effect of neglecting collisions between different principal quantum levels and the approximation can be shown to be valid when

$$P_{14} \gtrsim 10\, n_e x_{14} \qquad \text{... (10)}$$

The inequality can easily be satisfied for an expanding C$\underline{V}$ plasma in the spatial region between 1 and 3 mm from the surface of a laser-irradiated polyethylene target, Irons and Peacock (1974). In this target plasma $10 \text{ eV} < KT_e < 20 \text{ eV}$ and $10^{17}\text{cm}^{-3} < n_e < 10^{18}\text{cm}^{-3}$, $1 \times 10^{16} < N_g$ (C$\underline{V}$) $< 5 \times 10^{17}\text{cm}^{-3}$. The ratio for the pumping rate to the collisional excitation rate into the $n = 4$ level is given by

$$\frac{P_{14}}{x_{14} n_e} \simeq \frac{1}{\rho_4} \qquad e^{368\left(\frac{1}{KT_e} - \frac{1}{KT_p}\right)} \qquad \ldots (11)$$

where ρ_4 is the deviation from LTE for level 4 and is not far from unity. In equation (11) the LHS is at least 10^8 so that the inequality (10) is easily satisfied and collisonal processes can be ignored.

The line width of the CV̄ (4 - 1) transition at 2 mm distance from the target surface is mainly due to streaming motion with component, $\Delta\nu_D$, due to thermal motion about an order of magnitude smaller. Stark broadening is about an order of magnitude smaller again than the thermal component, Irons and Peacock (1974). In equation (4) then

$$B_{14}(\nu) = B_{14}\sqrt{\frac{\ln 2}{\pi}} \cdot \frac{1}{\Delta\nu_D} \cdot e^{-\left[\ln 2\,(\nu-\nu_0)^2/\Delta\nu_D{}^2\right]} , \qquad \ldots (12)$$

where the full half-width of the line due to thermal motion is $\Delta\nu_D \sim 3 \times 10^{12}$ c/s. Irons and Peacock (1974).

The super-radiant gain in the CV̄ pumped plasma at $\lambda = 186.70$ Å is therefore,

$$G = \left(\frac{\ln 2}{\pi}\right)^{\frac{1}{2}} \cdot \frac{A(1s2p - 1s4d)}{4\pi\,\Delta\nu_D} \cdot \lambda^2 \cdot \left(N_{1s4d} - \frac{N_{1s2p}\, g_4}{g_2}\right) \qquad \ldots (13)$$

$$\simeq 10^2 \text{ cm}^{-1}, \text{ with } \lambda \text{ in cm.}$$

Even with a target plasma whose typical dimension is a few mm, super-radiant emission along the pump axis should be observable.

It can readily be shown that a black-body source at a temperature of say 200 eV will optically pump almost all the ions in the target plasma. The absorption coefficient for the resonance transition is given by

$$K = \frac{A_{41}}{8\pi} \cdot \frac{\lambda^2{}_{41}}{\Delta\nu} \cdot N_g \; (C\underline{V}) \;\; cm^{-1} \qquad \ldots (14)$$

$\sim 10^4$ cm^{-1} for the C$\underline{V}$ (1 - 4) transition, with N_g (C$\underline{V}$) = 10^{17} cm^{-3}

Thus in a time of the order $(cK)^{-1} \sim 3 \times 10^{-15}$ secs the n = 4 level in a 1 μm layer of the plasma will have saturated. With a 4 nsecs laser pulse as used in recent experiments, Galanti and Peacock (1974), optical pumping could in principle cause saturation over an extensive plasma depth ~ 3 metres.

4. THE OPTICALLY-THICK LINE SOURCE

It has been shown by the authors, Galanti et al (1974), that the C$\overline{\underline{VI}}$ Lyman α emission from the surface of a polyethylene target irradiated by a high-powered laser is optically thick with an optical depth, τ, exceeding 50. The intensity of the emission corresponds to that of a black-body at a temperature equal to the electron temperature of the plasma in the critical density region, ie where the electron density is 10^{21} cm^{-3}. The emission originates from a narrow spatial region between 1 and 10 μm in depth and 300 μm in width. The latter dimension is essentially the diameter of the focal spot which is determined by the laser divergence and the focal length of the simple doublet lens used to focus the laser beam onto the target surface, Galanti and Peacock (1974). A typical profile of C$\overline{\underline{VI}}$ Lyman α is shown in figure 2. Absorption in the colder, peripheral plasma accounts for self-reversal in the central wavelength region of the line profile. The calculated peak emission with no reversal corresponds to black-body emission of 110 ± 10 eV as compared to the Lyman continuum measurement of 126 ± 6 eV for the free electron temperature, Galanti et al (1974). The half-intensity, half-width of the line $\Delta\lambda_{\frac{1}{2}\tau}$ is 0.023 Å. Scaling the opacity broadening with optical depth, and assuming a dispersion profile on the wings,

$$\Delta\lambda_{\frac{1}{2}\tau} = \Delta\lambda_{st} \, (\tau)^{\frac{1}{2}} \quad ,$$

where $\Delta\lambda_{st}$ is the dispersion half-intensity width and τ is the optical depth.

In order to extend the opacity-broadened half, half-width by 0.31 Å and thus overlap with the 33.426 Å C$\underline{V}$ transition, τ values $> 10^3$ are necessary and this can be achieved with plasma dimensions exceeding 1 cm or so.

A more accurate computation of the source profile is given by

$$I\,(\nu) = S_p\,(1 - e^{-\tau(\nu)}) \qquad \ldots (15)$$

where $\tau(\nu) = N_1 \, L(\nu) \, \frac{h_{\nu o,}}{c} \, B_{12} \, D$,

and S_p is the Planck function at the temperature of the plasma in the region of the critical density for resistive absorption. $N_1 cm^{-3}$ is the number of C^{5+} ions in the ground state, $\simeq 10^{20}$ cm^{-3}, (Galanti and Peacock, 1974);D cm, is the plasma dimension and $L(\nu)$ is the emission line shape within the plasma, which is determined by thermal and Stark broadening. Theoretical Stark profiles appropriate to the critical density region have been evaluated by Richards (1974). These profiles take into account both the impact approximation for electronic collisions and the effect of the ions with screening of the ion microfield. Vidal, Cooper and Smith (1973) have also tabulated Stark broadening parameters for hydrogen which with suitable scaling laws can be used to approximate Richard's values for C$\underline{VI}$ Lyman α. In the critical density region the doppler half-width exceeds the Stark width by about a factor of five for an electron temperature of 300 eV, a reasonable value for a carbon target plasma with incident laser flux intensities $\sim 3 \times 10^{12}$ watts/cm^2. The emission profiles have been calculated according to equation (15) for a range of plasma dimensions D and for a range of plasma temperature (ie incident laser flux intensities) in the critical density region. With plasma dimensions of $\gtrsim 1$ cm, $I(\nu)$, figure 2, readily overlaps the $n = 4 - 1$ transition in CV, $\Delta\lambda = 0.29$ AU'S. Saturation of the wings of the Lyman α at the black-body intensity is governed almost entirely by the important Stark wing profiles while, in this example, doppler broadening plays no significant role.

A line focus of dimension $\gtrsim$ 1cm, with a width of the order of 50 μm, can readily be achieved with a cylindrical lens. The light intensity may be maintained over this larger focal area at the same level as used to record the spectrum in figure 2 with a simple thirty-fold increase in laser brightness. The laser output power then required is $\sim 10^{11}$ watts and this is well within the capacity of several existing laser systems. If the He-like pumped line is also significantly broadened, see section 3, opacity broadening of the pump source can be relaxed somewhat.

5. SUMMARY AND DISCUSSION

From our previous work (see reference list) we recognise that the steep variation in the density and temperature of plasma produced at the surface of a laser-irradiated target may be used with advantage to create conditions of population inversion. In the critical density zone which is only of the order of a few microns in depth the lower members of the Lyman series can undergo substantial opacity broadening and this region of the plasma can be used as an efficient source for optically pumping resonance lines in an adjacent target plasma.

The target plasma is most conveniently produced by laser irradiation also, but here the spatial zone is a few mm in extent, and lies 1 to 3 mm from the target surface, where collisional processes between the levels of interest are unimportant. During the application of the incident laser pulse, which typically will last a few nanoseconds, almost all of the target ions which lie predominantly in the ground state will be optically pumped. Resonance pumping is therefore an extremely efficient process.

The principle has been considered with respect to inversion of the n = 4 levels relative to the n = 3 and n = 2 levels in C$\underline{V}$ using opacity-broadened C$\underline{VI}$ Lyman α as a pump source, since a considerable amount of quantitative spectroscopic data exists for laser-irradiated carbon surfaces (see references). However an overlap of the (1 - 3) N$\underline{VI}$ transition with N$\underline{VII}$ Lyman α would be considerably easier.

In order to keep the gain, equation (13), at a value above unity it is necessary to minimise losses due to the geometry of the emission source relative to the pumped plasma. We envisage that the source could be effectively immersed in the plasma using a stepped profile at the target surface as shown in figure 3.

The use of other ion species for opacity-broadened pumping readily suggest themselves, particularly when the pump source and target ions are from different elements. A possible scheme involves the excitation of the doubly excited levels whose transitions are satellite to the resonance lines of the H- and He-like ions in laser-produced plasmas, Peacock, Hobby and Galanti (1973). Several of these levels eg. $1s2p^2\ {}^2P^e$, are metastable to autoionisation and will be preferentially populated relative to the other autoionising levels. Resonance decay to the lower $1s^2\ 2p$ levels lie in the soft x-ray region. The $1s\ 2p^2\ {}^2P_{\frac{1}{2},\frac{3}{2}}$ levels of Al $\underline{XI}$, for example may be pumped with the $1s^2$ - 1s 3p Mg $\underline{XI}$ transition at 7.850 Å. In this case the wavelength difference is of the order $\sim .005$ Å. The attraction of this scheme is that the target plasma consists of cold, Li-like ions which can be produced with relatively modest laser flux intensities.

REFERENCES

Irons F E and Peacock N J, 1974(a), J.Phys.B: Atom. Molec.Phys. vol 7.No 15,2084-2099.

Irons F E and Peacock N J, 1974(b), J.Phys.B: Atom. Molec.Phys. vol 7 No.9. 1109-1112

Galanti M and Peacock N J, (1974), submitted to J.Phys.B: Atom. Molec.Phys.

Galanti M, Peacock N J, Norton B A and Puric J (1974). Paper CN-33-/F3-4 Proc. Fifth Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Nov. 1974. To be published, IAEA Vienna.

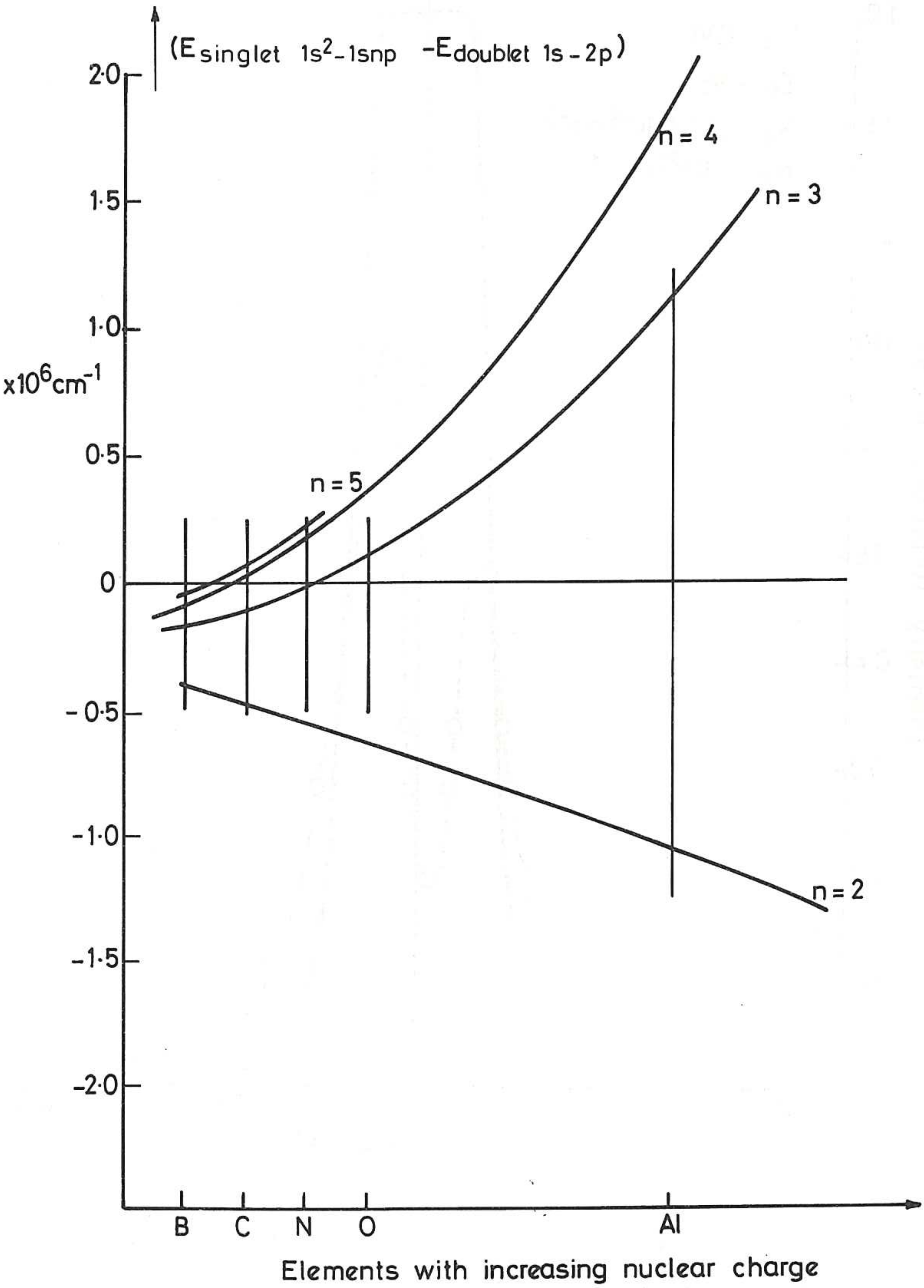
Bristow T C, Lubin M J, Forsyth J M, Goldman E B and Soures J M, 1974. Opt. Comm. 5, 315-8.

Duguay M A (1973), Laser Focus. Nov Issue, pp 41-46.

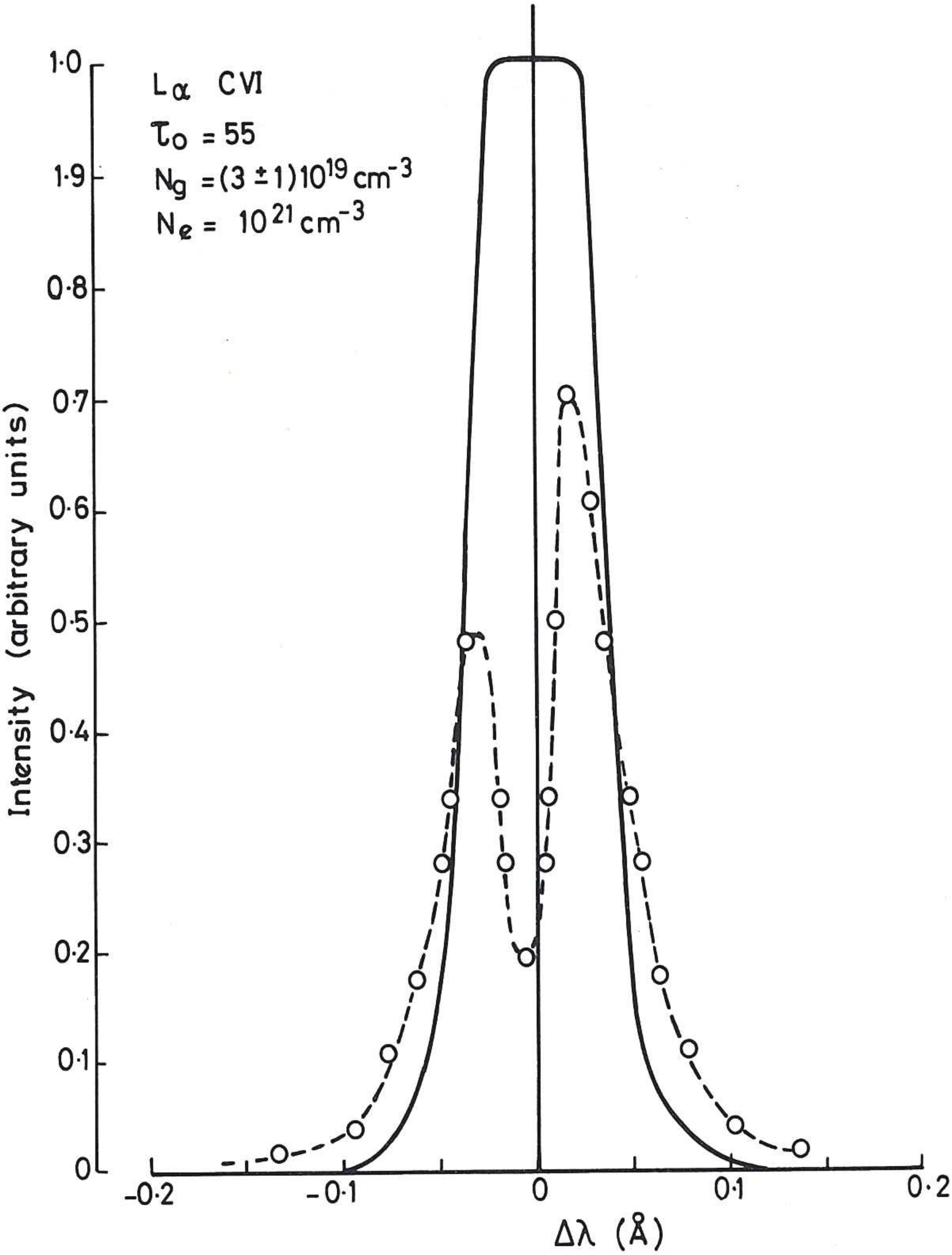
Peacock N J, Hobby M G and Galanti M (1973), J.Phys.B: Atom. Molec.Phys. 6, L 298-304

Richards A (1975) Ph.D. Thesis - London University - To be submitted.

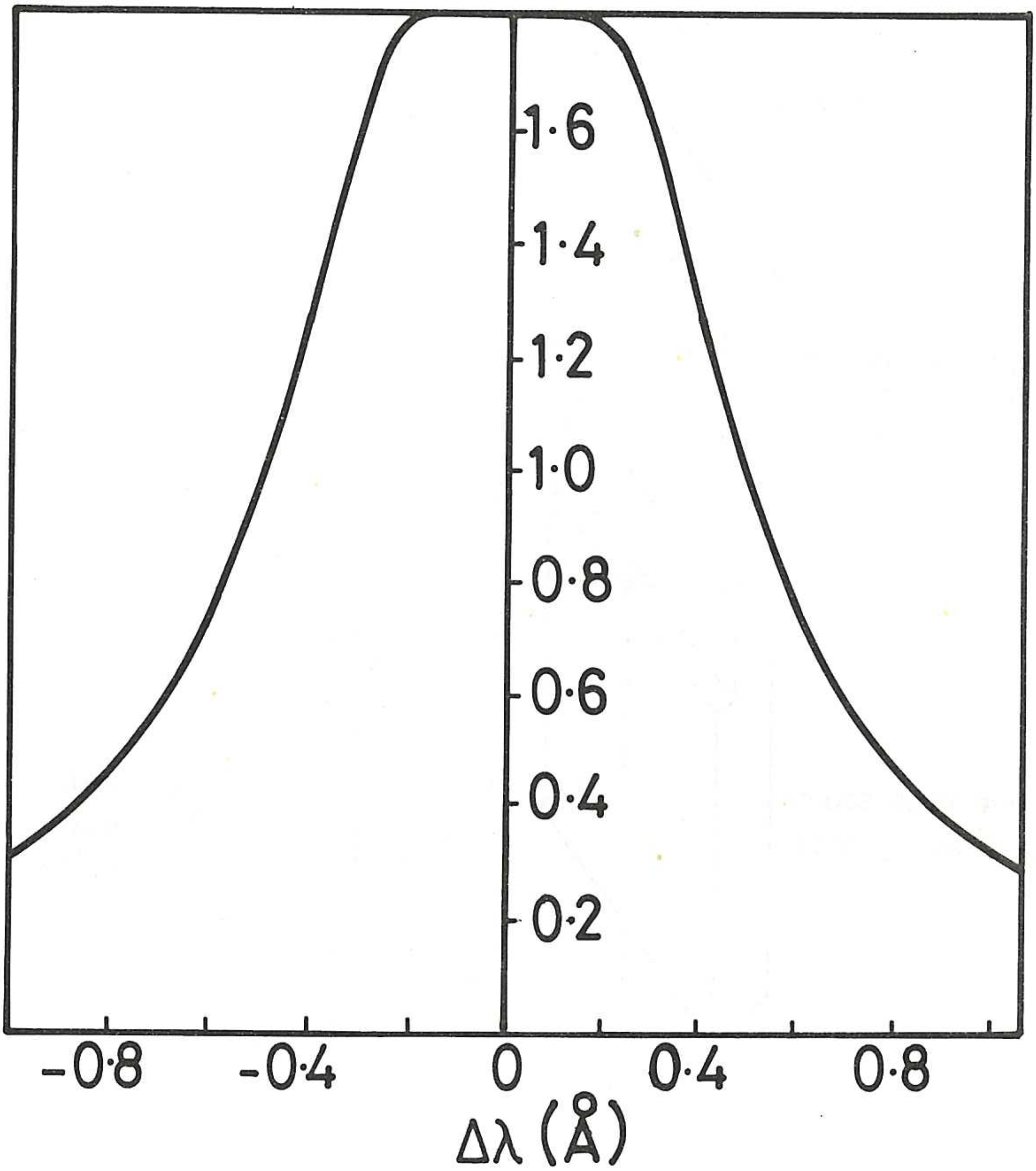
Vidal C R, Cooper J and Smith E W (1973) Astrophys. Jnl. Supp. No 214 25 pp.37-136.



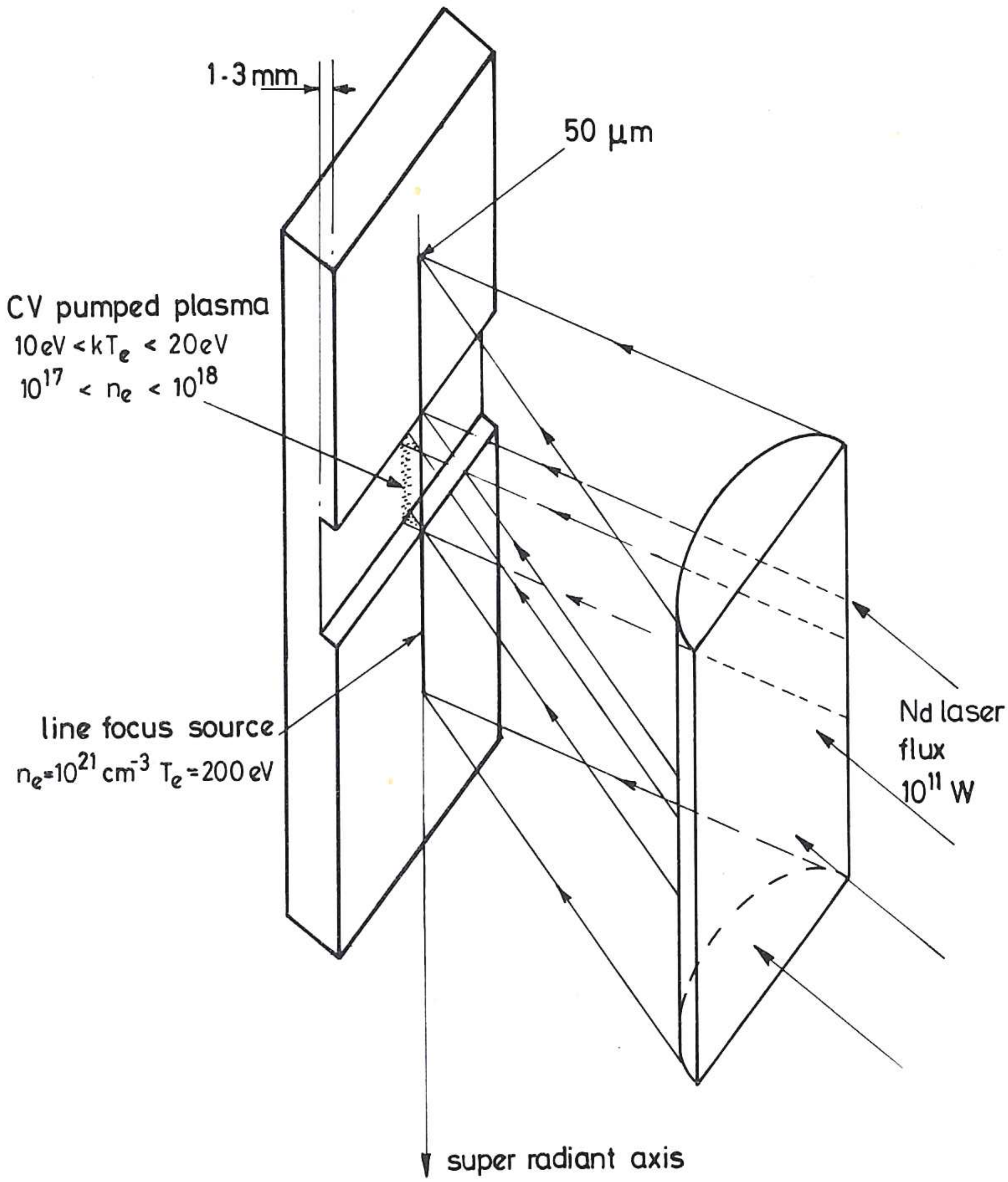
1. Energy difference, in wave numbers, between Lyman α of H-like ions and the He-like ion resonance transitions of the same element. 'n' denotes the upper principal quantum number of the He-like ion transition.



2(a). Experimental profile of Lyman α $C\overline{VI}$, from a 300 micron plasma dimension at the surface of a $(CH_2)_n$ target irradiated with a 10^{11} watts/cm^2, 1.06 μm, laser beam. The calculated profile (full line) has a peak intensity corresponding to a black body temperature of 112 eV. Broadening of the line results from opacity with an optical depth, τ = 55. Ng is the density of $C\overline{VI}$ ions in the ground level while Ne = 10^{21} cm^{-3}, is the critical density for resistive, radiant energy absorption.



2(b). Calculated Lyman $_\alpha$ C$\overline{\underline{VI}}$ profile for 1 cm plasma dimension at an electron density of 10^{21} cm^{-3} in a laser produced carbon plasma. The source profile is a Voigt function whose thermal component (half-intensity, half width) is $\delta\nu_D = 4 \times 10^{13}$ c/s and dispersion (Stark) component is $\delta\nu_S = 8 \times 10^{12}$ c/s. These parameters are typical of the critical density region of the plasma produced at a carbon surface by irradiation with 3×10^{12} watts cm^{-2} of 1.06 micron radiation, Galanti and Peacock (1974). The optical depth at the line centre is 2.1×10^{4}.



3. Schematic representation of 50 micron wide $C\overline{VI}$ pump source and a $C\underline{V}$ target plasma, both produced at a notched, solid, carbon surface irradiated by a neodymium laser. Super-radiance is expected along the length of the H-like ion source plasma.