Energy Transfer and Superradiance Between Two High Temperature Carbon or Nitrogen Plasmas

B. A. Norton

Physics Department, Royal Holloway College, Egham, Surrey, England

(Z. Naturforsch. **30 a**, 263–264 [1975]; received November 8, 1974)

Efficient superradiant wavelength conversion and focussing in the vacuum UV region below 300 Å is described for Carbon and Nitrogen plasmas. In this scheme a plasma containing predominantly Helium-like ions is pumped with optically thick resonance radiation from Hydrogen-like ions in a neighbouring plasma of higher temperature. Such a two-plasma system could exist in the earth's atmosphere, or in the laboratory by irradiating a suitable target with a high-powered laser. The power requirements in the latter case are within present capabilities.

Introduction

High density plasmas with electron temperatures between 100 eV and 600 eV have been produced in the laboratory by e. g. laser irradiation of solid targets in vacuum [1, 2]. With laser powers ranging from 0.4 MW to 200 MW [1], a plasma hemisphere of $\cong 1-2$ mm radius has been produced near to the target surface containing charged particles of density $\cong 10^{21}$ cm^{-3} and temperature $\cong 100$ eV. This dense plasma expands rapidly and becomes transparent to the laser radiation whilst injection of cold material from the target takes place. It is unlikely in these circumstances that the normal steady state ionization equilibrium for an isolated plasma will be reached in the dense region. If this region is sufficiently large and contains a significant number of incompletely stripped ions, the resonance lines of these will be optically thick and broadened to such an extent that they may overlap resonance transitions in other ions in neighbouring plasmas. A Hydrogen – Helium plasma system would be most efficient as the former ion emits strong resonance radiation whilst the latter is an ion with a large ionization potential following on from a succession of ions with low ionization potentials. This means that the secondary plasma is both easy to produce and maintain in a stable state.

The Pumped Plasma

Pumping rates in Helium-like ions decrease with principal quantum number n, in which case pumping will be most effective up to $n \cong 4$. By comparing the energy difference between the 1s – 2p Hydrogen-like transition and various resonance transitions in the Helium-like ion of different elements, it is found that the $n=4$ level in CV and the $n=3$ level in NVI lie the closest. For example, in order to produce a population inversion between the 4p and the $n=2, 3$ levels in CV, the $1s^2\,{}^1S - 1s4p\,{}^1P^0$ CV transition at 33.426 Å should be pumped by the opacity-broadened $1s\,{}^2S - 2p\,{}^2P^0$ CVI line whose central wavelength is at 33.736 Å. For a plasma of dimension ~ 1 mm with an electron temperature $\cong 200$ eV containing a large number of Hydrogen-like ions in the ground state, say $\cong 10^{19}$ cm^{-3}, the Lyman-alpha line would have an optical thickness τ_0 at the centre $\sim 10^2$. In these conditions the Stark effect will be the dominant broadening mechanism in the wings of the line. The Stark width $\Delta\lambda_S$ can be obtained for CVI by extrapolating from existing theoretical and experimental data for Hydrogen [3, 4]. When the optical opacity is large, the resulting half width of the line $\Delta\lambda_\tau$ is approximately

$$\Delta\lambda_\tau = \Delta\lambda_S \sqrt{\tau_0}\,. \qquad (1)$$

With a pumping rate from the ground level at least of the same order of magnitude as the reverse spontaneous decay rate (A) and with collisional transitions (X) into and out of the upper levels assumed negligible, the population densities (N) of the singlet $n=2, 3$ and 4 levels of CV are given by,

$$\frac{dN_4}{dt} = N_1 P_{1,4} - N_4 \sum_{q<4} A_{4,q} + N_1 N_e X_{1,4}\,, \qquad (2)$$

$$dN_3/dt = N_4 A_{4,3} - N_3 \sum_{q<3} A_{3,q} + N_1 N_e X_{1,3}\,, \qquad (3)$$

$$dN_2/dt = N_4 A_{4,2} + N_3 A_{3,2} + N_1 N_e X_{1,2} - N_2 A_{2,1}\,. \qquad (4)$$

The pumping rate (P) is defined by,

$$P_{1,4} = [g_4 A_{4,1} (\lambda_{4,1})^5 I_0] / g_1\, 2\, h\, c^2 \qquad (5)$$

where I_0, the flux intensity (W/cm^2, steradian, unit wavelength) of the pumping radiation, is assumed constant over the whole width of the CV transition.

In the case of strong pumping all the collision processes can be neglected in Eqs. (2) – (4) but all the sub-levels with the same value of n are assumed to be statistically populated. From Eq. (3) in the steady state,

$$N_4/N_3 = (A_{3,2} + A_{3,1}) / A_{4,3}\,, \quad \cong 37.2\, g_4/g_3\,. \qquad (6)$$

From Eqs. (3) and (4),

$$N_4/N_2 = [A_{2,1}(A_{3,2} + A_{3,1})] / [A_{4,2} (2 A_{3,2} + A_{3,1})]\,, \quad \cong 31.5\, g_4/g_2\,. \qquad (7)$$

Reprint requests to B. A. Norton, Physics Department, Royal Holloway College, *Egham, Surrey,* England.

In the absence of absorption by cooler surrounding plasma layers, the peak intensity of the broadened emission, i. e. I_0, will have the black-body value corresponding to the temperature of the plasma source ($k T_s$) in which case from Eq. (2),

$$N_4 \sum_{q<4} A_{4,q} = N_1 A_{4,1} \, g_4/g_1 (\exp\{h \nu_{1,4}/k T_s\} - 1) . \quad (8)$$

The neglect of the collision terms is justified if $P_{1,4}$ is $\gtrsim 10 N_e X_{1,4}$. If $10 \text{ eV} < k T_p < 20 \text{ eV}$ for the pumped plasma this inequality is satisfied if N_e is $\lesssim 10^{23} \text{ cm}^{-3}$. The requirement that collisional transitions do not compete with the radiative decay of level 4 puts an upper limit on $N_e \lesssim 10^{18} \text{ cm}^{-3}$. The line widths of the CV transitions can be assumed for illustration to be mainly governed by thermal motion, although Stark broadening can be estimated using the collision theory of Griem [3] which has been shown to describe adequately the widths of the lines from low lying levels in CIV ions [5].

The superradiant gain coefficient (G) in the pumped plasma at $\hat{\lambda} = 196.7$ Å, which is the strongest member of the 1s2p – 1s4d multiplet transition, is

$$G = (\ln \cdot 2/\pi)^{1/2} \left(\frac{A_{(1s\,2p - 1s\,4d)} \, \hat{\lambda}^2 \, (N_{1s\,4d} - N_{1s\,2p} \, g_4/g_2)}{4 \pi \, \Delta \nu} \right) . \quad (9)$$

Discussion

In high-power laser produced plasmas the electron density will at least reach the value at which the laser light is reflected (i. e. $\sim 10^{21} \text{ cm}^{-3}$ for a Neodymium laser) and the half width of the Lyman-alpha transition in CVI will be of the order 3×10^{-3} Å over a wide range of temperatures in the absence of opacity broadening. For this line to overlap the 33.426 Å CV line, τ_0 must be of the order 10^4. If $k T_s$ is $\cong 200$ eV then, from Eq. (8), N_4/N_1 in the pumped plasma will be ~ 1. With a CVI ground state ion density of $\sim 10^{19} \text{ cm}^{-3}$ a plasma source of dimension ~ 10 cm would be required. To produce a plasma of dimensions 10 cm $\times 0.1$ cm, at a temperature of $\cong 200$ eV, a laser power density $\gtrsim 10^{12} \text{ Wcm}^{-2}$ would be necessary. This requirement is within the capacity of modern laser systems [6]. The pumped plasma can easily be produced by diverting a small fraction of the main laser beam. If the ground state density of CV ions in this plasma is $\sim 10^{17} \text{ cm}^{-3}$ and $k T_p \cong 10$ eV, $G \cong 10^2 \text{ cm}^{-1}$.

It is evident that the two – plasma system described above would convert a fraction of the Neodymium laser pulse at wavelength 1.06 μm into vacuum UV radiation. It is also possible that this mechanism could be responsible for converting and focussing Lyman-alpha radiation from a hot Carbon or Nitrogen plasma. Consider a hot dense plasma cylinder or cone containing a high proportion of CVI or NVII ions which is surrounded by a cooler layer consisting mainly of the corresponding Helium-like ions. Optically thick Lyman-alpha emission from the core can pump the outer layer so that superradiant emission occurs in an axial direction in the form of an annulus. Large scale plasmas of this form may exist in space, or in the earth's atmosphere during a time of electrical activity. If the two plasmas experience a relative motion towards each other, for example if the inner core is rotating, the Doppler shift alone of the Lyman-alpha line may be sufficient for pumping purposes. At a relative velocity $\cong 10^8$ cm/sec the value of τ_0 in the core need only be $\cong 10$. Rotating plasmas with a velocity of 10^8 cm/sec have been produced in the laboratory [7].

1 N. G. Basov et al., Sov. Phys. JETP **24**, 659 [1967].
2 H. Opower and W. Press, Z. Naturforsch. **21 a**, 344 [1966].
3 H. R. Griem, Astrophys. J. **132**, 883 [1960].
4 R. C. Elton and H. R. Griem, Phys. Rev. **135**, A 1550 [1964].
5 P. Bogen, Z. Naturforsch. **27 a**, 210 [1971].
6 P. Mulser, Z. Naturforsch. **25 a**, 282 [1970].
7 D. M. Wetstone, Phys. Fluids **5**, 981 [1962].