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NEW ASPECTS OF X-RAY LASERS PUMPED BY PHOTOIONIZATION

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Abstract - It is shown that a steady state inversion on hydrogenic states can be obtained if a fully ionized plasma is subjected to the appropriate kind of radiation. Two well defined cases are numerically investigated:

1. narrow band pumping radiation,
2. black body pumping radiation.

Special emphasis is given to the question if radiative cooling of the plasma is sufficient to prevent a temperature increase of the electron gas which would destroy the inversion.

1. Introduction

In the photoionization-recombination equilibrium of hydrogenic ions, there is inversion between levels of different principal quantum number in appropriate parameter regions. It is analytically estimated /1,2/ that pump intensities available from the emission of a laser-produced plasma would be sufficient for generating substantial gain at wavelengths in the soft x-ray region.

In this paper, numerical calculations are presented which show that a decisive factor for the successful application of this scheme is the spectral composition of the pumping radiation. In particular, two special cases are investigated:

- narrow-band pumping radiation
- black-body pumping radiation.

A collisional-radiative model /3/ was used to calculate the population densities of ions in hydrogenic levels at given electron density and electron temperature. The pumping radiation is included by a removal rate from the various levels to the continuum, with appropriate correction for stimulated emission from the free electrons /4/. In the case of black-body radiation, radiative pumping between bound states is also taken into account.

Using the well-known hydrogenic Z-scaling (applicable if Gaunt factors are set equal to one) reduced number densities

\[ \eta(n) = \frac{B(n)}{Z^{10}} \]  

are calculated from the reduced plasma parameters

\[ \eta_e = \frac{N_e}{Z^7} \]  
\[ \theta_e = \frac{T_e}{Z^2} \]

where \( B(n) \) is the number of ions per cm\(^3\) in the level with principal quantum number \( n \), \( N_e \) is electron density and \( T_e \) is the electron temperature.
For the investigations presented in this paper the plasma was considered to be optically thin. Hydrodynamic motion of the plasma was neglected.

Special consideration was given to the power balance of the plasma by calculating the absorbed power from the pumping radiation and the emitted power into $4\pi$. It was checked whether the plasma at the specified electron temperature is in equilibrium with the pumping radiation, i.e. if radiation cooling is sufficient to balance the power absorbed from the pump.

2. Results for narrow-band pumping radiation

The pumping rate from level $n$ to the continuum is given by

$$\dot{\eta}(n) = P_n \{\eta(n) - 3.32 \times 10^{-22} n_e^2 \theta_e^{-3/2} \times \exp \left[-(h \nu / Z^2 - 13.6/n^2)/\theta_e \right]\}$$

(4)

where $P_n$ is the photoionization rate from level $n$, $h \nu$ is the energy of the pump photons in eV and $\theta_e$ is the reduced electron temperature in eV. The last term in the equation takes care of stimulated emission from the electron gas.

The relation between $P_n$ and the photon flux of the pumping radiation is

$$P_n = \sigma_n n \rho$$

(5)

where $n$ is the number of photons arriving at the plasma per cm$^2$ and $\sigma_n$ is the photoionization cross-section of ions in level $n$, given by /5/

$$\sigma_n = 2.76 \times 10^{20} Z^4/\nu^3 a^5 \left[\text{cm}^2\right]$$

(6)

By combining equs. (5) and (6) one obtains for the intensity of the pumping radiation

$$I_p = 8.2 \times 10^{-6} Z^8 \rho \left(h \nu / Z^2 \right)^4 \left[\text{W/cm}^2\right]$$

(7)

Results for the reduced electron temperatures $\theta_e = 2, 4$ and 6 eV are shown as "threshold isotherms" in Fig. 1, where the minimum pumping rate $P_1$ for obtaining inversion between the $n = 3$ and $n = 2$ levels is plotted versus the electron density. The solid lines correspond to regions where the power balance of the plasma is maintained with $h \nu / Z^2 \geq 13.6$ eV and where, therefore, equilibrium between the power absorbed from the pump and the power emitted by the plasma into $4\pi$ is possible in a physically realizable situation.

Inspection of Fig. 1 shows that there is a range of reduced electron densities between about $10^{12}$ and $10^{14}$ cm$^{-3}$ where the pumping rate is relatively low, readily identifiable as the region where three-body recombination preferentially populates the higher levels of the hydrogenic ions. At lower electron densities, radiative recombination dominates (thus populating low levels), whereas at higher electron densities mixing of the levels by electron collisions destroys the inversion.

Similar curves have been calculated for the inversion between $n = 4$ and $n = 3$. The pump power in this case is lower and the curves are slightly shifted to lower electron densities.

3. Black-body pumping radiation

The pumping radiation is specified by the temperature of the source $T_p$ and a transfer-factor $\mu \leq 1$. To make the results $Z$-independent, a reduced source temperature $\theta_p = T_p / Z^2$ is used.
Fig. 1: "Threshold isothermes" for narrow band pumping radiation. The electron temperature is constant along each curve. Above the curves one has $\Delta N_{32} > 0$, where $\Delta N_{32} = \eta(3)/g(3) - \eta(2)/g(2)$ is the reduced inversion between levels 3 and 2 and $g(n) = 2 n^2$ is the degeneracy of the levels. In the dotted portion of the curves power balance of the plasma is maintained only for $hv/2 < 13.6$ eV, where $hv$ is the energy of the pump photons. For the definition of $P_1$ see text.

With $\mu = 1$, one has $\theta_e = \theta$ and the levels are in Saha-Boltzmann equilibrium. To obtain inversion, however, $\mu$ must be considerably lower than $\theta_e$ if this be achieved simply by reducing the transfer factor $\mu$?

Figure 2 shows the situation for the examples $\theta_e = 20$ eV and $\theta = 2, 4$ and 6 eV. The figure plots the minimum $\mu$ required to obtain inversion at the specified $\theta - \theta_e$ combination. Also shown is the value of $\mu$ which would result in a power balance of the plasma, such that the power absorbed from the pumping radiation equals the power radiated by the plasma into $4\pi$. It is evident that at the $\theta - \mu_e$ values of

Fig. 2: "Threshold isothermes" for blackbody pumping radiation. Along each curve the combination for $\theta_e/\theta$ is constant and as indicated. The threshold isothermes above which $\Delta N_{32} > 0$ are in the upper part of the diagram. The "power balance isothermes", along which the indicated electron temperature is maintained by radiative cooling, are in the lower right corner. For the definition of $\mu$ see text.
the examples the "power balance $\mu$" is orders of magnitude lower than the "threshold" $\mu$ for all electron densities.

Many numerical runs with different $\theta-\phi$ combinations were performed, these consistently showing that the "power balance isotherm" never crosses the "threshold isotherm" for inversions between levels up to $n = 4$ and $\mu > 10^{-6}$. Even though no general law can be derived from numerical calculations, it is felt that parameter regions with inversion on hydrogenic levels in a plasma in equilibrium with any kind of thermal radiation are quite unlike to be found, unless the transfer factor $\mu$ is reduced to extremely low values.

4. Conclusion

Quasistationary inversion on hydrogenic levels is obtained by irradiating a plasma with high-power photoionizing radiation. Numerical calculations show that in the case of a narrow frequency distribution of the pumping radiation radiative cooling is sufficient to keep the electron temperature at a low enough value. Experimentally, this could be achieved by irradiating a plasma of low-Z ions with a group of lines emitted by a laser-produced high-Z plasma /6/. However, if black-body radiation is used as the pumping source, it becomes difficult to achieve inversion, since the electron gas gets heated beyond a temperature which would allow inversion to exist.

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References