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Soft X-ray laser emission from W^{46+}

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Abstract. Using published atomic data, the populations of the excited states $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^9\ 4l$ ($l = s$, p, d, and f) – $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}$ of Ni-like W have been calculated for electron densities in the range 10^{20}–10^{23} cm^{-3} and electron temperatures in the range 0.5–1 keV. For those transitions with positive population inversion factor, the gain coefficients are determined and plotted against the electron density.

PACS. 32.30.Rj X-ray spectra – 42.55.Vc X- and gamma-ray lasers

1 Introduction

Enhancement of efficiency is one of the major goals in the development of X-ray lasers. The high optical pump energy required to produce lasing at $\lambda < 15$ nm has restricted applications of X-ray lasers to a few large laser installations and for many years prevented achievement of X-ray laser saturation at shorter wavelengths [1]. Saturated operation of an X-ray laser is important because it means that the maximum power possible for a given volume of excited plasma is extracted by stimulated emission and usually it means that high drive efficiency is achieved. Although saturation has been observed at wavelengths of $\lambda > 15$ nm in neon-like X-ray lasers on the $3p\ ^3\mathrm{P}_2 \rightarrow 3s\ ^1\mathrm{P}_1$ and $3p\ ^1\mathrm{D}_2 \rightarrow 3s\ ^3\mathrm{P}_1$ (J= 2–1) transitions in plasmas of germanium [2], selenium [3] and yttrium [4] and on the $3p\ ^1\mathrm{S}_0 \rightarrow 3s\ ^1\mathrm{P}_1$ ($J = 0$–1) transition in zinc [5], argon [6], germanium [7] and titanium [8] plasmas, these X-ray lasers are difficult to scale to the shorter wave-lengths ($\lambda < 15$ nm) required for many applications because the driver energy needed to produce the gain-length product for saturation increases very rapidly in neon-like X-ray lasers for shorter wavelength operation [9]. Nickel-like X-ray lasers, in principle, have a much more favorable scaling of laser wavelength with drive energy as they have a higher quantum efficiency. Much effort was devoted towards developing nickel-like X-ray lasers using single long pulse [10,11] and multi-pulse drive configurations [12–14], but the resulting gain-length product and efficiency were, at first, still low. However, relaxing the density gradients in collisionally excited X-ray lasers through multiple pulse pumping has proved to be effective in enhancing drive efficiency [5,7,8,12–21].

The purpose of this work is to use the atomic data which are found in the literature to calculate reduced population of W^{46+} excited levels over a wide range of electron density and at various electron temperatures. The gain coefficients are also calculated.

2 Computation of gain coefficient

The possibility of laser emission from plasma of W^{46+} ion via electron collisional pumping, in the soft X-ray spectral regions is investigated at different plasma temperatures (0.5, 0.8 and 1 KeV) and plasma electron densities (from 10^{+20} to 10^{+23} cm^{-3}).

The reduced population densities are calculated by solving the coupled rate equations [22–25].

$$N_j\left[\sum_{i<j} A_{ji} + N_e\left(\sum_{i<j} C^d_{ji} + \sum_{i>j} C^e_{ji}\right)\right] = N_e\left(\sum_{i<j} N_i C^e_{ij} + \sum_{i>j} N_i C^d_{ij}\right) + \sum_{i>j} N_i A_{ij} \quad (1)$$

where N_j is the reduced population density of the jth level, A_{ji} is the spontaneous decay rate from jth level to ith level, C^e_{ji} is the electron collisional excitation rate coefficient, and C^d_{ji} is the electron collisional de-excitation rate coefficient, which is related to electron collisional excitation rate coefficient by [26,27]:

$$C^d_{ji} = C^e_{ij}\left[\frac{g_i}{g_j}\right]\exp\left[\Delta E_{ji}/KT_e\right] \quad (2)$$

where g_i and g_j are the statistical weights of lower and upper levels, respectively.

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The electron impact excitation rates are usually expressed via the effective collision strengths as

$$C_{ij}^{e} = \frac{8.6287 \times 10^{-6}}{g_i T_e^{1/2}} \gamma_{ij} \exp \frac{E_{ij}}{KT_e} \text{ cm}^3 \text{ s}^{-1} \tag{3}$$

where the values of γ_{ij} and A_{ji} are obtained by [28].

The actual population density, N_J of the jth level is obtained from the identity,

$$N_J = N_j N_I \tag{4}$$

where N_I is the quantity of ions which reaches the ionization stage, and is given by [29]

$$N_I = f_I \frac{N_e}{Z_{avg}} \tag{5}$$

where f_I is the fractional abundance of the nickel-like ionization stage as calculated by Goldstein et al. [29], N_e is the electron density, and Z_{avg} is the average degree of ionization.

Since the populations calculated from equation (1) are normalized such that,

$$\sum_{J=1}^{55} \left(\frac{N_J}{N_I}\right) = 1 \tag{6}$$

where 55 is the number of all the levels of the ion under consideration, the quantity actually obtained from equation (1) is the fractional population N_j/N_I.

After the calculation of level population, the quantities N_u/g_u and N_l/g_l can be calculated.

After collision, the lasant ion plasma will transfer the pumped quanta to other levels, and will result in population inversions between the upper and lower levels. Once a population inversion has been ensured a positive gain, i.e $F > 0$ [30] is obtained:

$$F = \frac{g_u}{N_u} \left[\frac{N_u}{g_u} - \frac{N_l}{g_l}\right] \tag{7}$$

where $\frac{N_u}{g_u}$ and $\frac{N_l}{g_l}$ are the reduced populations of the upper and lower levels respectively. Equation (7) has been used to calculate the gain coefficient "α" for Doppler broadening of the various transitions in the W^{46+} ion.

$$\alpha = \frac{\lambda_{lu}^3}{8\pi} \left(\frac{M}{2\pi K T_i}\right)^{1/2} A_{ul} N_u F \tag{8}$$

where M is the ion mass, $\lambda_{\ell u}$ is the transition wavelength in cm, T_i is the ion temperature in K is assumed to be 0.67 of the value of the electron temperature and u, l represent the upper and lower transition levels respectively.

The gain coefficient is expressed in terms of the upper state density (N_u). This quantity depends on how the upper state is populated, as well as on the density of the initial source state. The source state is often the ground state for a particular ion.

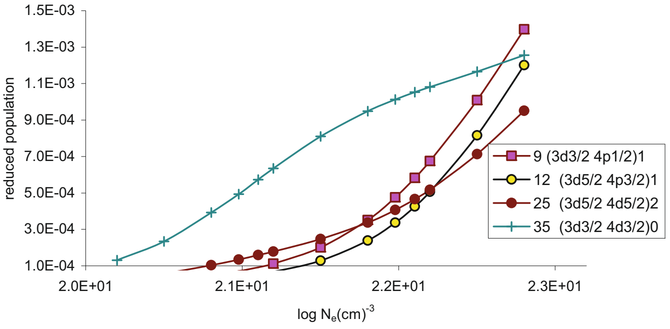

Fig. 1. (Color online) Reduced population of W^{46+} levels after electron collisional pumping as a function of the electron density at temperature of 0.5 KeV.

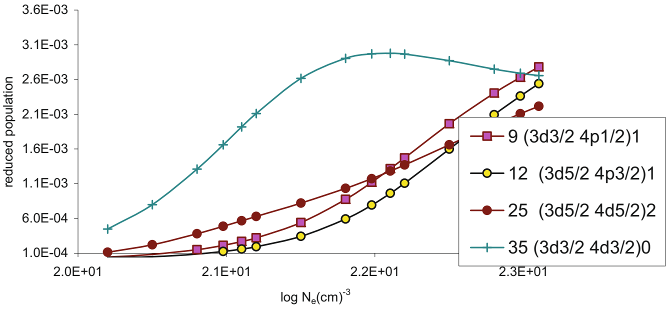

Fig. 2. (Color online) Reduced population of W^{46+} levels after electron collisional pumping as a function of the electron density at temperature of 0.8 KeV.

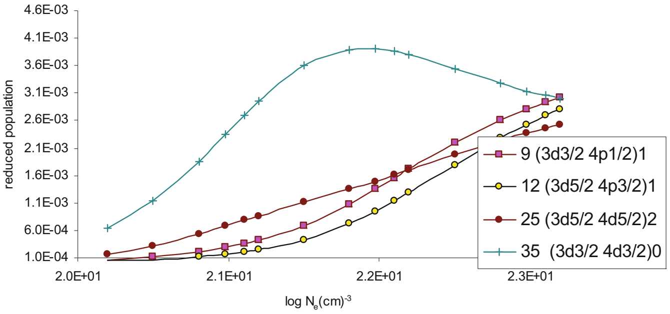

Fig. 3. (Color online) Reduced population of W^{46+} levels after electron collisional pumping as a function of the electron density at temperature of 1.0 KeV.

3 Results and discussions

3.1 Level population

The atomic structure and effective collision strength data were taken from reference [31] then the reduced population densities are calculated for 55 fine structure levels arising from $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^9\ 4l$ ($l = s$, p, d, and f) – $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}$ by solving the coupled rate equations (1) using MATLAB version 7.3.0 computer program for solving simultaneous coupled rate equations.

Our calculations for the reduced populations as a function of electron densities are plotted in Figures 1–3 at three different plasma temperatures (0.5, 0.8, 1.0 KeV) for W^{46+} ion.

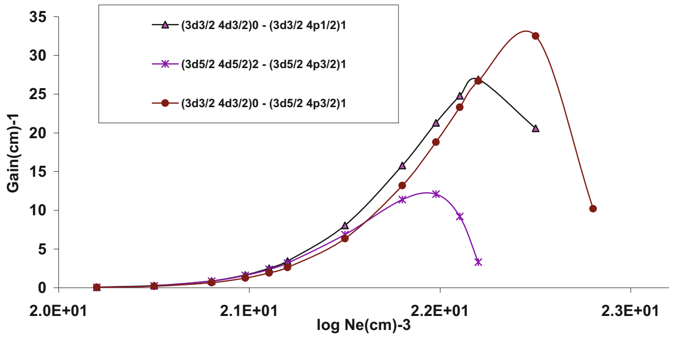

Fig. 4. (Color online) Gain coefficient of laser transitions against electron density at temperature of 0.5 KeV in W^{46+}.

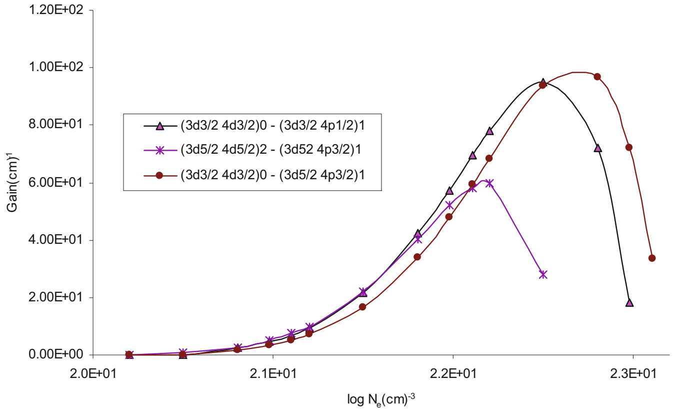

Fig. 5. (Color online) Gain coefficient of laser transitions against electron density at temperature of 0.8 KeV in W^{46+}.

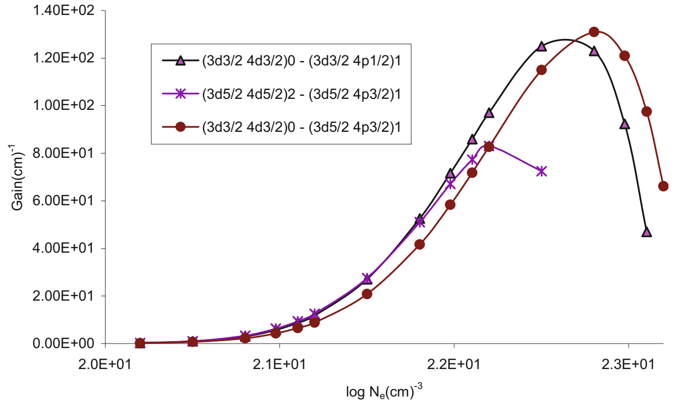

Fig. 6. (Color online) Gain coefficient of laser transitions against electron density at temperature of 1.0 KeV in W^{46+}.

In the calculation we took into account spontaneous radiative decay rate and electron collisional processes between all levels under study.

The behavior of level populations of the various ions can be explained as follows: in general, at low electron densities the reduced population density is proportional to the electron density, where excitation to an excited state is followed immediately by radiation decay, and collisional mixing of excited levels can be ignored. This result is in agreement with that of Feldman et al. [24,25,32]. At high densities ($N_e > 10^{23}$), radiative decay to all levels will be negligible compared to collisional depopulations and all level populations become independent of electron density and are approximately equal. The $(3d_{3/2}\ 4d_{3/2})_0$ level shows a peak at electron density of 6×10^{21} cm^{-3} before the other levels, then decrease to the saturation faster than the other levels which mean that the nonradiative transitions dominant the deexcitation since it has higher energy and a fast decay time (see Figs. 1 to 3). The population inversion is largest where the electron collisional deexcitation rate for the upper level is comparable to the radiative decay for this level [24,32].

3.2 Inversion factor

As we mentioned before, laser emission will occur only if there is population inversion, or in other words, for positive inversion factor $F > 0$. In order to work in the soft X-ray spectral region, we have selected transitions between any two levels producing photons with wavelengths between 50 and 150 Å. The electron density at which the population reaches collisional equilibrium approximately equal to A/D, where A is the radiative decay rate and D is the collisional de-excitation rate [24]. The population inversion is largest when the electron collisional deexcitation rate for the upper level is comparable to the radiative decay rate for this level.

3.3 Gain coefficient

As a result of population inversion there will be a positive gain in laser medium. Equation (8) has been used to calculate gain coefficient for the Doppler broadening of various transitions in the W^{46+} ion.

Our results for the maximum gain coefficient in cm^{-1} for those transitions having a positive inversion factor $F > 0$ in the case of W^{46+} ion at different temperatures are calculated and plotted against electron density in Figures 4–6. Figures show that the population inversions occur for several transitions in the W^{46+} ion, however, the largest gain occurs for the W^{46+} ion is at $(3d_{3/2}\ 4d_{3/2})_0$–$(3d_{5/2}\ 4p_{3/2})_1$ transition.

These short wavelength laser transitions can be produced using plasmas created by optical lasers as the lasing medium.

For W^{46+} ion the rates for electron collisional excitation from the $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}$ ground state to the $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^9\ 4d$ configuration are higher than the rates for excitation from the ground state to the $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^9\ 4p$ state.

For electron densities and electron temperatures that are typical of laboratory high-density plasma sources, such as laser produced plasmas, it is possible to create a quasistationary population inversion between the $3d^9\ 4d$ and $3d^9\ 4p$ states in W^{46+} ion. Our calculations have shown that under favorable conditions large laser gains for this transition in the soft X-ray region of the spectrum can be achieved in the nickel like W ion. The gain calculations

Table 1. Parameters of the most intense laser transitions in W^{46+} ion plasma.

Lazer Transition	t_u (ns)	t_l (ns)	T_e (eV)	λ (Å)	α (cm^{-1})	N_e (cm^{-3})
$(3d_{3/2}\ 4d_{3/2})_0$–$(3d_{3/2}\ 4p_{1/2})_1$	6.80E-04	1.60E-40	500	42.8	26.9	1e224E+21
$(3d_{5/2}\ 4d_{5/2})_2$–$(3d_{5/2}\ 4p_{3/2})_1$	3.07E-03	8.00E-05	500	86.9	12.1	6.00E+21
$(3d_{3/2}\ 4d_{3/2})_0$–$(3d_{5/2}\ 4p_{3/2})_1$	6.80E-04	8.00E-05	500	47.7	32.5	2.00E+22
$(3d_{3/2}\ 4d_{3/2})_0$–$(3d_{3/2}\ 4p_{1/2})_1$	6.80E-04	1.60E-04	800	42.8	95	2.00E+22
$(3d_{5/2}\ 4d_{5/2})_2$–$(3d_{5/2}\ 4p_{3/2})_1$	3.07E-03	8.00E-05	800	86.9	60	1.00E+22
$(3d_{3/2}\ 4d_{3/2})_0$–$(3d_{5/2}\ 4p_{3/2})_1$	6.80E-04	8.00E-05	800	47.7	96.5	4.00E+22
$(3d_{3/2}\ 4d_{3/2})_0$–$(3d_{3/2}\ 4p_{1/2})_1$	6.80E-04	1.60E-04	1000	42.8	125	2.00E+22
$(3d_{5/2}\ 4d_{5/2})_2$–$(3d_{5/2}\ 4p_{3/2})_1$	3.07E-03	8.00E-05	1000	86.9	83.1	1.00E+22
$(3d_{3/2}\ 4d_{3/2})_0$–$(3d_{5/2}\ 4p_{3/2})_1$	6.80E-04	8.00E-05	1000	47.7	131	4.00E+22

t_u is the radiative lifetime of upper laser level in nanosecond;
t_l is the radiative lifetime of upper laser level;
T_e is the electron temperature in eV;
λ is the wavelength of laser transition in Å;
α is the gain coefficient in (cm^{-1});
N_e is the electron density in (cm^{-3}).

were performed at electron temperatures equal to 500, 800 and 1000 eV at different electron densities. It is obvious that the gain increases with the temperature.

The two transitions $(3d3/2\ 4d3/2)_0$–$(3d5/2\ 4p3/2)_1$ and $(3d3/2\ 4d3/2)_0$–$(3d3/2\ 4p1/2)_1$ for $J=$ 0–1 emission line were observed experimentally by Daido et al. [33] using, 1.053 μm laser pulses with total energy of 200–500 J. However, the lower gain coefficient of $\sim$3 cm^{-1} obtained by them is dependent on the experimental conditions.

4 Conclusion

The analysis that has been presented in this work shows that electron collisional pumping (ECP) is suitable for attaining population inversion and offering the potential for laser emission in the spectral region between 50 and 150 Å from the W^{46+} ion. This class of lasers can be achieved under the suitable conditions of pumping power as well as electron density. If the positive gains obtained previously for some transitions in the ion under study (W^{46+} ion) together with the calculated parameters could be achieved experimentally, then successful low cost electron collisional pumping soft X-ray lasers can be developed for various applications. The results have suggested the following laser transitions in the W^{46+} plasma ion (see Tab. 1), as the most promising laser emission lines in the soft X-ray spectral region.

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