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Modelling of the Ni-like and Co-like line emission from Ni-like Silver X-ray laser media

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Abstract. We have modelled the Ni-like and Co-like resonance lines emitted from Ni-like Silver X-ray laser media using a collisional radiative code. The code calculates intensities of Ni-like $1s^22s^22p^63s^23p^63d^{10} \longrightarrow 1s^22s^22p^63s^23p^63d^9\ nl$, Co-like $1s^22s^22p^63s^23p^63d^9 \longrightarrow 1s^22s^22p^63s^23p^63d^8\ nl$ resonance lines emitted from silver. Intensities of photons emitted between Ni-like $1s^22s^22p^63s^23p^63d^9\ n'l' \longrightarrow 1s^22s^22p^63s^23p^63d^9\ nl$ and Co-like $1s^22s^22p^63s^23p^63d^8\ n'l' \longrightarrow 1s^22s^22p^63s^23p^63d^8\ nl$ excited levels are also calculated. The optimum electron temperature and density for $J = 0 - 1$ lasing at 13.9 nm is evaluated. The ratios of Co-like 3d–4p to Ni-like 3d–4p resonance lines are calculated with the aim that such ratios can serve as a diagnostic to measure electron temperatures.

1. Introduction

Saturation in the Ni-like Silver X-ray laser at 13.9 nm has been reported [1–4]. Several techniques have been used to achieve saturated Ni-like X-ray lasing, namely double target arrangements [1], single picosecond pump pulses [3], double pulse pumping with both longer and picosecond pulses [5]. An understanding of the kinetic properties of Ni-like and Co-like Silver is of fundamental importance for current X-ray lasers. The dynamics of laser-produced plasma parameters such as the electron and ion temperatures and the density can be modelled by fluid hydrodynamic codes [6, 7]. Modelling of the emission from laser-produced plasma has been performed either with a co- or post-processor [8] to the hydrodynamic codes or simply by assuming a single set of plasma parameters (i.e. electron density and temperature). We have adopted this approach here and present results for electron densities between 10^{18} and 10^{21} cm^{-3} and electron temperatures between 100 and 700 eV for steady state conditions. For some time-dependent calculations, we assume that the electron temperature first increases from a low temperature to 250 eV, then decreases exponentially at an electron density equal to the Nd:YAG critical density 10^{21} cm^{-3}.

We modelled the Ni-like and Co-like resonance lines emitted from Ni-like Silver X-ray laser media, using the collisional radiative model. The code [9] calculates intensities of Ni-like and Co-like resonance lines emitted from silver plasma. We have also calculated the gain coefficient for the Ni-like silver lasing line at

13.9 nm. The resonance line ratio emitted from a plasma can be used to determine the electron temperature and electron density, so we evaluated the ratio of Co-like 3d–4p to Ni-like 3d–4p resonance lines using the collisional-radiative model.

2. Method of solution

Densities of atoms for specific ionization stages are determined by rate equations for the balance between ionization and recombination. For ionization stage $i+ (i = 1, 2, 3, \ldots, Z-1, Z)$ where the $Z+$ ion is completely stripped, the necessary equation for the populations N of ionization stages takes the form [10]

$$\begin{aligned}\frac{dN^i}{dt} = N_{\mathrm{e}} \left\{ N^{i-1} I^{i-1} + N^{i+1} \left[R_{\mathrm{rr}}^{i+1} + N_{\mathrm{e}} R_{\mathrm{cr}}^{i+1} + R_{\mathrm{de}}^{i+1} \right] \right. \\ \left. - N^i \left[I^i + R_{\mathrm{rr}}^i + N_{\mathrm{e}} R_{\mathrm{cr}}^i + R_{\mathrm{de}}^i \right] \right\} \qquad (2.1)\end{aligned}$$

here I and R represent ionization and recombination rate coefficients. The subscripts rr, cr and de stand for radiative, collisional and dielectronic recombination, respectively. N_{e} is electron density. After calculating the particular ion density as above, the population densities of specific energy levels are calculated by solving a rate equation which includes all possible populating and depopulating mechanisms. A general form of rate equation for a specific excited level m is given by [10]

$$\begin{aligned}\frac{dn_m}{dt} = \sum_k \{ n_k \left[N_{\mathrm{e}} C_{km} + A_{km} + B_{km} u(\lambda_{km}) \right] - n_m N_{\mathrm{e}} (C_{mk} + B_{mk} u(\lambda_{km})) \} \\ + N_{\mathrm{e}} \left\{ N^{i-1} I^{i-1} - N_i I^i + N^{i+1} \left[R_{\mathrm{rr}} + N_{\mathrm{e}} R_{\mathrm{cr}} + R_{\mathrm{de}} \right] \right\} \qquad (2.2)\end{aligned}$$

where $N_{\mathrm{e}} C_{km}$ and A_{km} represent respective electron collisional excitation and spontaneous radiative decay rates from an arbitrary level k to a lower specific level m, B_{km} and B_{mk} represent photo excitation and photo de-excitation, respectively, and $u(\lambda_{km})$ is the radiation energy density.

Equations (2.1) and (2.2) are transformed to linear algebraic equations system by applying an implicit finite-difference method. Equations system (2.1) is tridiagonal linear, so the fractional population of each ionic stage from neutral to bare nuclei can be solved by Crout reduction [11]. Equations system (2.2) is solved by the Gauss–Siedel iterative method [11]. The details of these methods are given in [9]. The ionization energies and statistical weights for each ion, the absorption oscillator strengths and excited level energy and statistical weights for all levels are obtained from the Cowan code [12]. 222 Ni-like $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}$ and $1s^2 2s^2 2p^6 3s^2 3p^6 3d^9\ nl$ $(n = 3\text{–}5, l = \mathrm{s, p, d})$ levels, 507 Co-like $1s^2 2s^2 2p^6 3s^2 3p^6 3d^9$ and $1s^2 2s^2 2p^6 3s^2 3p^6 3d^8\ nl$ $(n = 3\text{–}5, l = \mathrm{s, p, d})$ levels are considered in the calculation of the plasma emission. For steady state calculations, the solution of the matrix equations is performed by using a standard set of routines to first decompose the matrix into a upper triangular matrix. This is achieved using Gauss elimination. The results of this decomposition are then used to efficiently determine the answer solving with backward substitution.

All rate coefficients used in (2.1) and (2.2) are obtained supposing that the electron distributions are Maxwellian. These rate coefficients, i.e. ionization, recombination, collisional excitation and de-excitation, spontaneous emission coefficients are given in [9]. In this paper, (2.1) and (2.2) also include photo excitation and

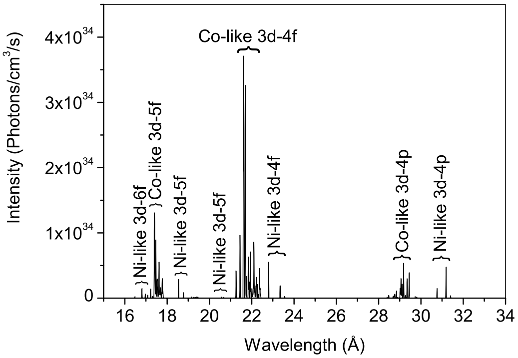

Figure 1. Ni-like and Co-like silver time-integrated resonance line spectrum.

de-excitation rates. After calculating the ions density and excited levels density, resonance line intensities emitted from the plasma are calculated by

$$I_k = n_k \frac{hc}{\lambda_0} A_{km} T \frac{\Phi(\lambda_0)}{\Delta\lambda} \tag{2.3}$$

where n_k is the upper state population for a given transition, h is Plank's constant, c is the vacuum speed of light, λ_0 is the spectral line wavelength, T is an escape factor to allow for radiation re-absorption in the plasma, $\Phi(\lambda_0)$ is the line shape function and $\Delta\lambda$ is line width. When population inversion occurs between 4d–4p levels, the lasing line intensity is evaluated by

$$I_k = n_k \frac{hc}{\lambda_0} A_{km} \exp(GL) \frac{\Phi(\lambda_0)}{\Delta\lambda} \tag{2.4}$$

where G is gain coefficient and L is plasma length. The other lines intensity is multiplied by escape factor evaluated using the Holstein approximation [13].

3. Results and discussion

A pre-pulse and double pulse are applied to get saturated X-ray lasers [5]. The pre- pulse produces a low-level ionized plasma. Then the plasma expands and electron density gradient becomes more uniform. The short pulse interacts with the preformed plasma. Since the electron temperature increases rapidly, population inversions occur in a short time. In our simulation, we used a low initial electron temperature to calculate the ion densities. The electron temperature is assumed to change with time at the Nd:YAG laser critical density. By increasing the electron temperature suddenly to 250 eV at 500 ps, we calculate the gain and resonance lines intensities as a function of time as the electron temperature decreases exponentially assuming that the electron density is fixed at the critical density. The Ni-like and Co-like ions dominate the plasma ionization.

Figure 1 shows the time-integrated resonance line silver spectrum evaluated with these assumptions. A Gaussian shaped line profile is assumed in the simulation of spectrum. The line width is calculated including the Doppler and Stark broadening effects. The ion temperature used in the calculation of the Doppler line width is assumed to be one-half of the electron temperature. Figure 2 shows gain coefficients and resonance lines intensities as a function of time. The calculated peak gain using

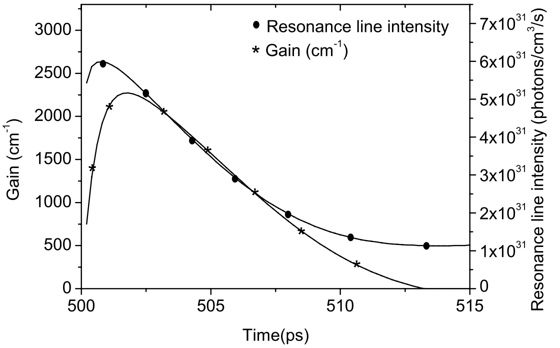

Figure 2. Gain and resonance lines intensities.

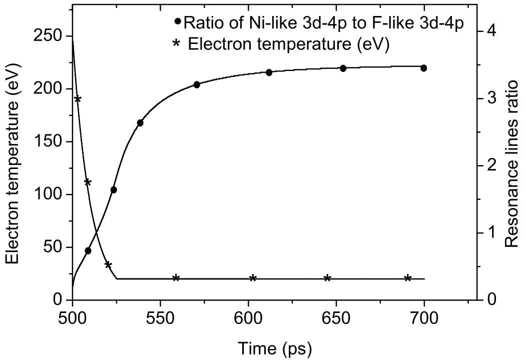

Figure 3. The ratio of Co-like to Ni-like 3d–4p resonance lines calculated at Nd:YAG laser critical density.

atomic data obtained from the Cowan code [12] is approximately 2500 cm^{-1}. In the simulation, the full width at half maximum (FWHM) of the Ni-like $J = 0$–1 line gain is found to be approximately 8 ps. The Ni-like silver X-ray laser pulse duration (FWHM) for silver was measured as 3.7 (±0.5) ps [14]. The simulated result supports the measured Ni-like silver laser pulse duration. The resonance line emission variation in time is similar to the gain coefficient variation as a function of time.

The excited levels in the Ni-like collisional X-ray laser media are populated mainly by electron collisions. Therefore, electron temperatures can be obtained using the resonance line intensity ratios. Since the Co-like and Ni-like 3d–4p lines are strong in the spectrum (Fig. 1), we evaluated the ratio of Co-like 3d–4p lines to Ni-like 3d–4p resonance lines as a function of time as in Fig. 3. We have calculated the ratio of Co-like resonance lines to Ni-like resonance lines assuming steady state collisional-radiative conditions for electron densities between 10^{18} and 10^{21} cm^{-3} and electron temperature between 100 and 700 eV (Fig. 4). The gain coefficient has a peak value at around 250 eV assuming an electron density 5×10^{20} cm^{-3}.

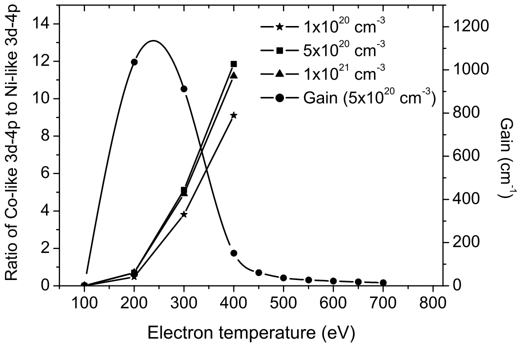

Figure 4. The ratio of Co-like to Ni-like 3d–4p resonance lines and gain coefficients calculated in steady state condition.

4. Conclusions

We modelled the Ni-like and Co-like resonance lines emitted from Ni-like silver X-ray laser media using a collisional radiative code. In steady state simulations, the optimum electron temperature is around 250 eV for maximum gain. At peak gain, the resonance line ratio of Co-like to Ni-like 3d–4p lines is approximately two. The gain coefficient variation in time is similar to the resonance line emission as a function of time.

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