Time dependent atomic processes in discharge produced low Z plasma

M. Yuyama, T. Sasaki, K. Horioka, and T. Kawamura
Department of Energy Sciences, Tokyo Institute of Technology, Nagatsuta 4259, Midori-ku, Yokohama, 226-8502, Japan

Abstract. The z-pinch simulation have been performed with magneto-hydro dynamics and atomic population kinetics codes. A factor associated with transient atomic processes was proposed. The atomic transient degrees of dopant lithium in hydrogen plasma were calculated with initial plasma densities of $1.0 \times 10^{16} \sim 5.0 \times 10^{17}$ cm$^{-3}$. The higher initial plasma density is, the lower is the transient degree generally. It is also found that the transient properties of the atomic processes are sensitive to ionization energy and electron temperature.

1. Introduction

The discharge produced plasma (DPP) with z-pinch scheme have been studied for the development of short wavelength light source. There have been many studies for z-pinch plasma with numerical simulations. They are helpful to understand the dynamics of z-pinch plasma and to find the optimum condition for the light source with high efficiency.

It is one of the issues that the transient properties of atomic processes affect the emission processes. Duston et al. simulated z-pinch plasma with magneto hydro dynamics (MHD) code [1]. In this paper collisional radiative (CR) and local thermal equilibrium (LTE) models are used. Their results show that LTE model is inadequate at ion density of $10^{17}$ cm$^{-3}$, and electron temperatures of up to about 30 eV in lithium plasma. Sawada et al. examined the validity of the quasi-steady-state solution in the rapid change of electron temperature [2]. Masnavi et al. calculated the non-equilibrium atomic processes of Ne-like Ar in optically thin plasma [3]. It is indicated that the fast heating of plasma lead to the higher gain for $J = 0 - 1$ line ($\lambda = 46.9$ nm) compared with steady state plasma.

In DPP with z-pinch scheme for the short wavelength light source, electron density increases to $10^{17} \sim 10^{20}$ cm$^{-3}$ and electron temperature increases to $1 \sim 10^2$ eV at the maximum compression of which time-scale in about $1 \sim 10^2$ ns. Therefore, atomic processes are transient in the range of plasma parameters, and depend on the time histories of plasma parameters. In this paper, we report the transient properties of atomic processes in z-pinch plasma. The transient degree of the atomic processes of dopant lithium in hydrogen plasma was calculated. The transient atomic processes influence the $1s - 2p$ emission (13.5 nm) of Li$^{2+}$ seriously. And we investigated the relation between the transient degree of atomic processes and the initial plasma condition.
2. Theoretical model and simulation conditions

The time evolution of z-pinch plasma were calculated by a 1-D cylindrical MHD code. The code treats two temperatures and one fluid model including electron-ion relaxation and thermal conduction. In the calculation of the population kinetics, rate coefficients were obtained in Kawamura et al. [4], and energy levels and oscillator strengths can be obtained through the web-site organized by NIST [5].

To evaluate the atomic processes, a post process scheme was adopted. With assumption that a fully ionized hydrogen plasma doped by a small mount of lithium, overall plasma fluid is not affected by the atomic processes of lithium. The fraction of the lithium atoms is 1 % of a total ion density. In the simulation, the time histories of plasma were calculated with the MHD code. The atomic processes of lithium were calculated using the plasma history, and the atomic equilibrium and non-equilibrium solutions were obtained for lithium.

3. Numerical results and discussions

The numerical MHD calculation was carried out with external discharge current $I(t) = I_0 \sin(\omega t)$, where $2\pi/\omega = 400$ ns and $I_0 = 100$ kA. The plasma was initially assumed to be uniform with the electron density $n_e(0) = 1.0 \times 10^{16} \text{ cm}^{-3}$, and the electron and ion temperatures $T_e(0) = T_i(0) = 0.1 \text{ eV}$. The initial capillary radius $r_0$ was 1 cm with the plasma velocity $u(0) = 0$. In the calculation, the plasma consists of fully-ionized hydrogen and lithium ions. The fraction of lithium is 1% of all ions.

Figure 1 shows the temporal evolution of the electron density and temperature at the point of which initial position $r = 0.6$ mm. The thermal and magnetic pressures determine the overall dynamics of the z-pinch. Magnetic pressure generated by the external discharge current is lager than the thermal pressure at the beginning. When the shock wave arrives at the z-axis, the plasma temperature is increased quickly. In the calculation, the shock wave arrives at the z-axis at 64 ns. After stagnation of the plasma near the z-axis, the kinetic energy of plasma is thermalized. In Fig.1, the electron temperature is increased up to 185 eV at 73 ns. At 74 ns, the electron density is increased up to $9.6 \times 10^{17} \text{ cm}^{-3}$. After the compression phase, the thermal pressure is larger than the magnetic pressure. The plasma begins to expand and to be cool down.

Figure 2 shows the time evolution of the average ionization degrees of lithium in the compression phase. In the calculation, the post process treatment was adopted for the population kinetics of lithium atoms. In Fig.2, the average ionization degrees obtained by a time-dependent and a steady state approximations are presented. From 9 ns to 32 ns, the difference between them can be found. During the time, Li$^{1+}$ is producted due to the joule heating, and the atomic processes are transient.

To discuss the transient atomic processes, the transient degree $F$ is proposed as follows,

$$F = \frac{1}{\tau z} \int_{t_1}^{t_2} |\bar{z}_{\text{eq}} - \bar{z}_{\text{neq}}| dt$$

where $z$ is an atomic number of target material, and $\bar{z}_{\text{eq}}$ and $\bar{z}_{\text{neq}}$ are respectively average ionization degrees of atomic equilibrium and non-equilibrium states. $\tau$ stands for $t_2 - t_1$. The equilibrium condition is not valid at the larger F. In the estimation of F, the time-interval between the shock arrival at the z-axis and the maximum electron density $n_{e \text{ max}}$ was taken as $\tau$. In general, the higher electron density leads atomic processes to equilibrium state and the smaller F.

With a steady state approximation, lithium atoms are fully stripped at 67 ns. On the other hand, in the time-dependent calculation, lithium atoms are fully stripped at 74 ns. Then the
**Figure 1.** The temporal evolution of temperature and density at the point of which initial radial position \( r = 0.6 \) mm.

**Figure 2.** The temporal evolution of the average ionization degrees at the point of which initial radial position \( r = 0.6 \) mm.

**Figure 3.** The temporal evolution of the 1\( s \) - 2\( p \) emission of Li\(^{2+}\).

**Figure 4.** Dependence of a transient degree on initial plasma densities.

**Table 1.** Relation between initial electron densities and time-histories of plasma. \( T_e \text{ max} \) and \( n_e \text{ max} \) are respectively the maximum electron temperature and density. \( \tau_p \) is the time-interval between the shock arrival at the z-axis and the maximum electron density.

| \( n_e(0) \) \((\times10^{16}\text{ cm}^{-3})\) | \( n_{e \text{ max}} \) \((\times10^{17}\text{ cm}^{-3})\) | \( T_{e \text{ max}} \) \(\text{(eV)}\) | \( \tau_p \) \(\text{(ns)}\) |
|---|---|---|---|
| 1.0 | 9.6 | 185 | 9 |
| 5.0 | 16.6 | 110 | 14 |
| 10.0 | 17.3 | 70 | 18 |
| 50.0 | 69.5 | 13.4 | 17.5 |
transient degree F is 0.25 (t=65 ∼ 74 ns). The F indicates that the average ionization degree differ by 0.75. Figure 3 shows the 1s - 2p emission of Li\textsuperscript{2+}.

With the steady state approximation, the 1s - 2p emission begins to appear at 66 ns, and the intensity increases with the increase in ion density after 68 ns. In the time-dependent calculation, the 1s - 2p emission appears around 68 ∼ 74 ns. The total 1s - 2p emission from the non-equilibrium solution \( \int E_{\text{neq}} \, dt \) is \( 1.4 \times 10^3 \) times larger than the equilibrium case \( \int E_{\text{eq}} \, dt \). It can be understood that the actual ionization processes are slow with the z-pinch scheme. Therefore, the large amount of Li\textsuperscript{2+} can be kept, even if the plasma temperature becomes high (\( \sim 100 \) eV), at which a lithium atom is fully ionized under the equilibrium condition. And the 1s - 2p emission can be large.

Figure 4 is given to see the dependence of F on initial electron densities and table 1 shows the relation between initial electron densities and time-histories of plasma. The higher initial electron density \( n_e(0) \) is, the higher is the maximum electron density \( n_e \text{ max} \), the lower is the maximum electron temperature \( T_e \text{ max} \), and the longer is the time-interval \( \tau_p \). The plasma heating becomes slow along with increase in the initial electron density, and the atomic processes approach the equilibrium condition, resulting in small F. However, in both \( n_e(0) = 5.0 \times 10^{16} \text{ cm}^{-3} \) and \( n_e(0) = 1.0 \times 10^{17} \text{ cm}^{-3} \) the transient degrees F are almost same. \( T_e \text{ max} \) with \( n_e(0) = 1.0 \times 10^{17} \text{ cm}^{-3} \) is smaller than that with \( n_e(0) = 5.0 \times 10^{16} \text{ cm}^{-3} \). Because the 1s - 2p transition energy of Li\textsuperscript{2+} is 91.6 eV, the fraction of the free electrons to ionize Li\textsuperscript{2+} is small in the case of \( n_e(0) = 1.0 \times 10^{17} \text{ cm}^{-3} \).

4. Conclusion

The transient degree of atomic processes F is proposed. The transient degree of lithium atoms in z-pinch process is sensitive to a time-history of plasma with initial plasma densities of \( 1.0 \times 10^{16} \sim 5.0 \times 10^{17} \text{ cm}^{-3} \), \( \omega I_0 = 1.57 \times 10^{12} \text{ A} \cdot \text{rad} \cdot \text{s}^{-1} \), and \( r_0 = 1 \text{ cm} \). The higher electron density leads the transient degree to small. The transient degrees of atomic processes also depend on the electron temperature and the ionization energy of a target ion, and drastically affect the 1s - 2p emission of Li\textsuperscript{2+}. And we are now studying the relation between plasma parameters and the transient radiative properties with F clearly.

References
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