High-precision measurement of the spectral width of the nickel-like molybdenum x-ray laser

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Abstract. In this study, we performed the first measurement of the spectral width of a nickel-like molybdenum x-ray laser (λ = 18.895 nm) by use of a high-resolution spectrometer. The intrinsic and amplified spectral width were measured to be 36 and 18 mÅ under the substantial lasing conditions, respectively. It corresponds to a temporal coherence of the amplified x-ray laser of 0.34 ps.

1. Introduction

In recent years, the advent of high-performance ultra short pulse lasers has made it possible to generate the high-brightness compact x-ray lasers (XRL) [1-3] based on laser-produced plasmas. The gain media of the plasma x-ray lasers are highly charged ions in high-density plasmas. Only a few measurements of the spectral width of the XRL have been reported [4,5], because the spectral width of the XRL is so narrow that the required spectral resolution is quite high, e.g. Δλ/λ ~ 10⁻⁴. The precise knowledge about the wavelength and the spectral width of the lasing line is important for the atomic physics and applications of the XRL. First, the spectral width is a good benchmark for the atomic code because it depends on the electron collisional impact excitation and de-excitation rate coefficient. Second, the spectral width shows the temporal coherence of the XRL. Temporal coherence is important for the applications such as the holography or diffraction imaging [6,7]. Third, the spectral width is an important parameter to determine the strength of the magnetic field required for the generation of the circularly polarized XRL. The circularly polarized XRL will be useful for the light source of the circular dichroism measurement [8]. The details of the circularly polarized XRL are described in section 5.

In this study, we choose the Ni-like Mo XRL (3d⁹4d ¹S₀ – 3d⁹4p ¹P₁) as an example and measured the spectral width by using a high-resolution spectrometer. Reasons for using this laser are: First, this laser line is in the wavelength region in which Mo/Si multi-layer mirrors have substantial reflectivity; therefore, this laser line is important for applications. Second, the strong amplification of this laser line has been obtained in previous work [2], and the high precision measurement can be obtained. Third, since the Ni-like Mo XRL media is the high electron density plasma, it is expected that the influence of stark broadening becomes dominant. In addition, we produced the XRL by using the
grazing incident pumping scheme (GRIP) [3]. GRIP scheme can control the electron density of the gain region of the x-ray laser. It implies that the experimental result can be compared with the theoretical one easily.

2. Experimental set-up

The experimental set-up is shown in figure 1. The nickel-like molybdenum x-ray laser was measured by the high-resolution spectrometer, HIREFS made by Hettrick scientific [9].

2.1. Pumping laser system

We used the GRIP scheme [3] for the focusing system of the Nd:glass laser at a wavelength of 1053 nm. GRIP scheme can control the electron density \( n_e \) of the laser absorption region by the grazing angle \( \theta \) to the target surface. The electron density of the laser absorption region is described to be \[ n_e = n_{cr} \sin^2 \theta \] where \( n_{cr} \) is the critical electron density and it is \( 10^{21} \text{ cm}^{-3} \) for the laser with the wavelength of 1053 nm. The grazing incidence angle was 14 degree, and the electron density of the laser absorption region was \( 6 \times 10^{19} \text{ cm}^{-3} \). The focal width and length were measured to be 70 \( \mu \text{m} \) and 5 mm, respectively. Nd:glass laser light consists of two pulses, the pre-pulse and the main pulse. The total energy on the target was 10 J, and the energy ratio of these pulses was 1 : 4. The pulse separation was 1.1 ns, and each duration was 7ps.

2.2. High-resolution spectrometer (HIREFS).

HIREFS has a spherical and elliptical mirror to transfer the image of the slit on to the detector. The magnification of the horizontal plane (= the direction of the plasma expansion) and the vertical plane (= the direction of the wavelength dispersion) were 2.4 and 3.2, respectively. The back-illuminated CCD (Princeton, PI-SX:1K, pixel size 13\( \mu \text{m} \)) was used for the detector.

The carbon spectrum was measured to decide the inverse linear dispersion of HIREFS. Carbon Balmer \( \alpha \) line (182.20 Å) and Ni-like Mo XRL line (188.95 Å) [10] were used for calibration. The inverse linear dispersion was measured to be 785 mÅ /mm on the CCD surface. The resolution of the HIREFS was estimated to be 12.7 mÅ \((d\lambda/\lambda = 7 \times 10^{-5})\) from the inverse linear dispersion, CCD pixel size, slit size \((= 3 \mu \text{m})\) and magnification of HIREFS \((= 3.2)\).

![Figure 1. Experimental set-up.](image)

3. Experimental result

Figure 2 shows the spectral profiles of the nickel-like molybdenum x-ray laser line at gain length product \((gl)\) were 3.1 (a) and 6.9 (b). Each dot and the solid curve show the data point and the fitting curve with the Voigt profile [4], respectively. The detail of the Voigt fitting curve is described in section 4. The spectral width of the XRL was measured to be 36 (a) and 18 mÅ (b) at the center wavelength of 18.895 nm.

Figure 3 shows the gain narrowing behavior of the spectral width of the Ni-like Mo XRL. Each XRL spectra were fitted by the Voigt profile. The spectral width was clearly increased at the gain length product of less than 4.
4. Discussion

The intrinsic spectral profile of the XRL is determined by convolution of the homogeneous and inhomogeneous broadening, e.g., Voigt profile. Homogeneous broadening (= $\Delta \omega_0$ (full width at half maximum: FWHM)) is determined by the depopulation rate of the lasing levels. Inhomogeneous component is due to Doppler broadening (= $D_0$ (FWHM)). The spectral profile, $f(\omega)$, was described by the convolution of these broadening.

$$ f(\omega) = \frac{2 \ln 2 \Delta \omega_l}{\pi^{3/2} \Delta \omega_D} \int_{-\infty}^{\infty} \frac{\exp(-4 \ln 2(\omega_0 - \omega_0^*)^2 / \Delta \omega_0^2)}{(\omega_0^* - \omega)^2 + (\Delta \omega_L / 2)^2} \mathrm{d} \omega_0^* $$

$\omega$ and $\omega_0$ were angular frequency and angular frequency of the wavelength center, respectively. The Doppler broadening is written by the ion temperature ($T_i$), ion mass ($m_i$) and light velocity ($c$); $\Delta \omega_d / \omega_0 = (8 \ln 2 kT_i / (m_i c^2))^{0.5}$. The typical plasma parameters in the present experiment were calculated by the 1-D hydrodynamic code HYADES [11]. The ion temperature ($T_i$), electron temperature ($T_e$) and electron density ($n_e$) were 60 eV, 400 eV and $6 \times 10^{19}$ cm$^{-3}$, respectively. It implied the Doppler broadening ($\Delta \lambda_d$) was 12 mÅ. We supposed the spectral profile at $gl = 3.1$ to be the intrinsic spectrum of the lasing line without gain narrowing effect. The intrinsic spectrum (figure 2 (a)) was fitted by the Voigt profile with homogeneous width ($\Delta \lambda_h$) of 30 mÅ. The amplified XRL spectrum (figure 2 (b)) was fitted by the Voigt profile with $\Delta \lambda_d = 6$ mÅ and $\Delta \lambda_h = 15$ mÅ. From this result, the temporal coherence of the intrinsic and the amplified XRL dominated by the homogeneous broadening were about 0.17 ps and 0.34 ps, respectively. In the previous experiment, the duration of the Ni-like Mo XRL was measured to be 2.5 ps [12], it implies the coherent photon ratio of the amplified XRL (= temporal coherence / duration) was 0.34 / 2.5 = 0.14.

Now we considered the theoretical spectral width of the homogeneous broadening ($\Delta \lambda_h$) from the result of the calculation for the Ni-like Ag x-ray laser line by HULLAC code ($\Delta \lambda_h$ = 18 mÅ at $\lambda = 13.9$ nm) [13,14]. Homogeneous broadening mainly depended on the depopulation rate of the lasing levels. They were estimated from the value for the Ni-like Ag case using the scaling law [15]; $C_i = Z^3 C_i^0$, where $C_i$ is the collisional rate coefficient for ion $Z$ and $C_i^0$ is the reduced collisional rate coefficient for $Z = 1$. In this calculation, $C_i^0 = 6.53 \times 10^{12}$ s$^{-1}$ at $n_e$ = $4.0 \times 10^{20}$ cm$^{-3}$. It red to be the theoretical width of Voigt profile was 20 mÅ with homogeneous width ($\Delta \lambda_h$) of 13 mÅ and inhomogeneous width of 12 mÅ. The theoretical broadening was small compared with the experimental result. The cause of the difference might be that the XRL was generated in high electron density region.

5. Future plan, generation of circularly polarized x-ray laser

The nickel-like ion x-ray laser ($4p$ ($J = 1$) - $4d$ ($J = 0$)) has three degenerated states (magnetic sublevel: $m = -1, 0, 1$) in the lower level. If the quantization axis is parallel to the longitudinal axis of the XRL media due to a strong magnetic field, the polarization of the XRL can be selected...
automatically. Left handed circularly ($\sigma', \Delta m = -1$) and right handed circularly polarized ($\sigma, \Delta m = 1$) x-ray laser will be generated. Each circular polarization can be selected by a spectrometer because of the different wavelength of each polarization by the Zeeman effect under influence of the strong magnetic field. The value of the Zeeman split ($\Delta \varepsilon$) is described to be $\Delta \varepsilon = 2.8 \mu_B B$, where $\mu_B$ is the Bohr magnetron ($= 5.8 \times 10^{-5} \text{eV/T}$), and $B$ is the strength of the magnetic field. From the measurement of the spectral width of Ni-like Mo XRL, the strength of the magnetic field required for the splitting of the circular polarization component was estimated to be 40 T. The pulse-power magnet system [16] for the next experiment is now under construction.

6. Summary

We have measured the precise spectral width of the nickel-like molybdenum x-ray laser. The intrinsic and amplified spectral width were 36 mÅ and 18 mÅ at the wavelength of 18.895 nm, respectively. It implies the temporal coherence of the intrinsic and amplified XRL were 0.17 ps and 0.34 ps, respectively. From this result, the strength of the magnetic field for the generation of circularly polarized x-ray laser was obtained (40 T). In the next work, we will try the generation of the circularly polarized x-ray laser with the pulse power magnet.

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