Generation of the Circularly Polarized X-Ray Laser Using the Pulse-Power Magnet

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Abstract. We proposed the method of generation of the circularly polarized x-ray laser using the Zeeman splitting. External magnetic field of 20 T was applied to the gain medium plasma to separate the degenerated lines of nickel-like molybdenum x-ray laser. The splitting of the x-ray laser line was clearly obtained, and the strength of the magnetic field estimated from the quantity of the x-ray laser line splitting was quite higher compared with that of the external magnetic field. It implies that there might be alternative mechanism for enhancement of the magnetic field in the gain medium plasma.

1 Introduction

The polarized light sources are used for the analysis of the structure of many materials in the wavelength region of the visible and hard x-ray. In particular, the circular dichroism measurement is very useful to analyze the 3-D structure of the materials, such as classification of the optical isomer (chirality) [1]. The circular dichroism measurement is basically absorption spectroscopy, so the use of intense soft x-ray sources such as x-ray lasers (XRL) is desirable to improve the sensitivity of the measurement. In the wavelength region of visible and hard x-ray, transmission optics can be used as phase control devise [2] to obtain circularly polarized light. Whereas in the wavelength of the soft x-ray region, there is no appropriate transmission optics. Recently, the circularly polarized soft x-ray has been generated by as a combination of synchrotron and undulators [3], however still large facility is required. Thus the investigation of alternative compact method to obtain circularly polarized soft x-ray is quite important. In the following, we propose the new approach for the generation of circularly polarized XRL by use of the external magnetic field.

2 Circularly polarized XRL by use of the external magnetic field

We considered the transition of the XRL to generate the circularly polarized XRL. Figure 1 shows the Kastler diagram of the nickel-like XRL line. The XRL is generated between the *4d* (J = 0) and the partial *4p* (J = 1) levels. There are three magnetic sublevels with m_J = -1, 0, 1 in the lower level, and the XRL has three degenerated lines. The polarization of these lines are left-handed circular (σ'), linear (π) and right-handed circular polarization (σ). The direction of the radiation of the circular components and linear component are parallel and perpendicular to the quantization axis, respectively. If we take the quantization axis to the direction of the external magnetic field, the circularly polarized XRL can be extracted. If the strength of the magnetic field is large enough to separate each polarization component by the Zeeman effect, each circular polarization can be extracted separately after resolving with high-resolution spectrometer. The quantity of the Zeeman shift is proportional to the strength of the magnetic field (see in section 3.1).

The schematic figure of the method of the extraction of the circularly polarized XRL is shown in Fig. 2. In this setup (the direction of the magnetic field is parallel to the axis of longitudinal of x-ray laser medium), the left- and right-handed circularly polarized XRL can be propagated in the XRL medium. The advantage of this method is that the right- and left-handed circularly polarized XRL are obtained at the same time.

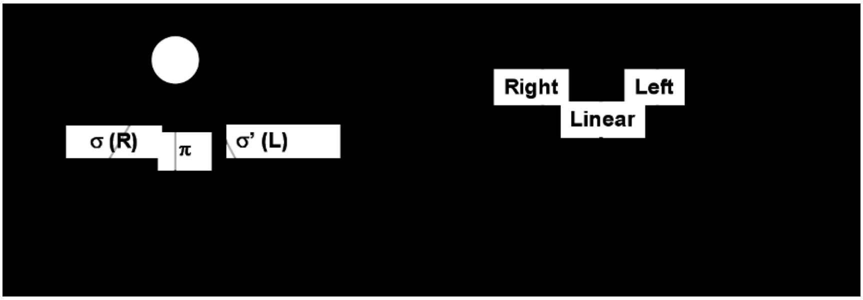

Fig. 1 Kastler diagram of the nickel-like XRL.

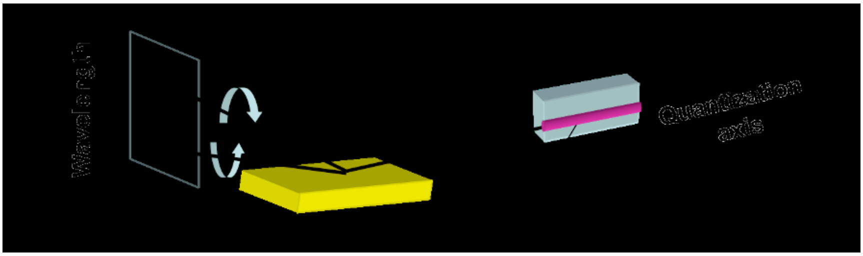

Fig. 2 Schematic diagram of the extraction of the circularly polarized XRL.

3 Experiment of the extraction of the circularly polarized XRL

In this study, we choose the Ni-like Mo XRL ($3d^9 4p\ ^1P_1 - 3d^9 4d\ ^1S_0$) as an example. The reasons for using this laser are as follows: the strong amplification has been obtained with the grazing incident pumping scheme (GRIP) [4] in previous work [5], and the wavelength can be covered by high-resolution spectrometer.

There were three steps to extract the circularly polarized XRL. First, we estimated the strength of the magnetic field required for the extraction of the circularly polarized XRL. Second, we made the pulse-power magnet system. Thirdly, we demonstrated the extraction of the circularly polarized XRL.

3.1 The strength of the magnetic field required for the extraction of the circularly polarized XRL

The Zeeman effect of the degenerated lines of highly charged ions such as XRL line can be treated by linear Zeeman effect and the quantity of the split is described as to be $2\Delta\varepsilon = \{J(J+1)\}^{1/2}\mu_B B$ (= 1.6×10^{-4} B eV), where μ_B is the Bohr magnetron (= 5.8×10^{-5} eV/T), and B is the strength of the magnetic field. To extract the each circularly polarized XRL component, the Zeeman split value has to be larger than the spectral width of the XRL without the external magnetic field.

Figure 3 shows the spectral profile of the nickel-like molybdenum x-ray laser line taken by the high-resolution spectrometer, HIREFS [6], without the external magnetic field. Each dot and the solid curve show the experimental data point and the fitting curve with the Gaussian profile, respectively. The detail of the experimental setup is described in section 3.3. The spectral width of the XRL ($d\lambda_{XRL}$) was measured to be 0.00205 nm ($d\lambda_{XRL} / \lambda_{XRL} = 1.1 \times 10^{-4}$). Consequently the magnetic field required for the splitting of the circular polarization components was estimated to be 45 T. To obtain this value is not difficult by using pulse-power magnet system [7].

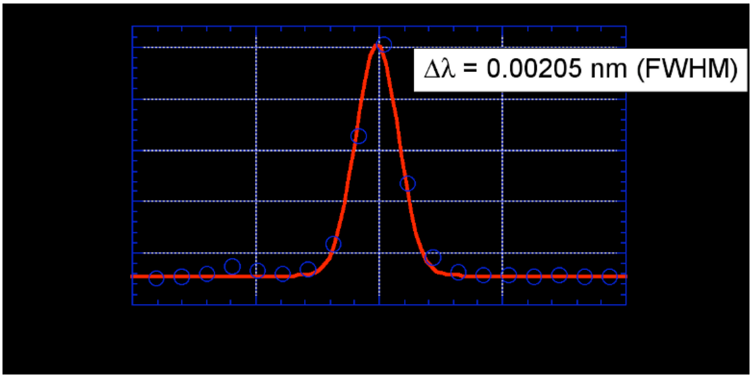

Fig. 3 The spectrum of the Ni-like Mo XRL.

3.2 The design of pulse-power magnet system

Figure 4 shows the scheme of the pulse-power magnet system. This system consists of five parts, DC power supply, capacitor, switching device, transmission line and solenoid coil. The coil, the transmission line and the capacitance of the system were designed to obtain the impedance matching between the coil and the capacitor. The impedance of this system was designed about 1 Ω. The inner diameter, length and the number of turn of the coil were 4 mm, 5 mm and 10, respectively. The electric current of 26 kA could produce 45 T magnetic field at the center of the coil. The width and thickness of the transmission line were 50 mm and less than 1 mm, respectively. The capacitance was 330 nF. As for the switching device, the laser triggered spark gap (LTSG) [8] was used. The characteristics of LTSG, i.e., tolerance for the large current and high voltage, fast switching (< 100 ns) and low jitter (< 10 ns) suited for the pulse power system. Nd:YAG laser at a wavelength of 532 nm was used for the trigger laser, and it was synchronized to the pumping laser of the XRL. The duration and energy of the trigger laser were 7 ns and 10 mJ, respectively. The magnetic field of 45 T could be obtained at the 30 kV charge.

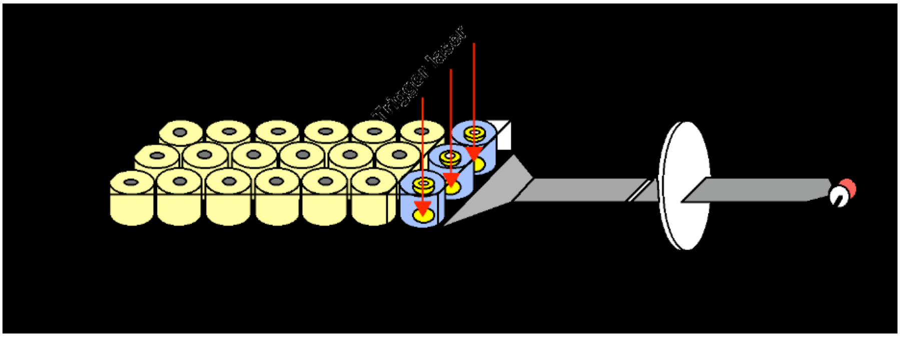

Fig. 4 Pulse-power magnet system.

3.3 Demonstration of the extraction of the circularly polarized XRL

We demonstrated the extraction of the circular polarized Ni-like Mo XRL. The experimental setup is shown in Fig. 5. The target was a thin rod (the cross section is 1 mm × 1mm and length is 30 mm) molybdenum to set at the center of the magnet coil. The peak value of the external magnetic field was estimated to be 20 T in the present experiment estimated from the temporal profile of applied voltage at the transmission line. Nd:glass laser at a wavelength of 1053 nm was weakly focused on the target surface under the grazing incident pumping (GRIP) configuration [4]. The grazing incidence angle was 14 degree, and the focal width and length were 70 μm and 5 mm, respectively. Nd:glass laser light consisted the pre-pulse and the main pulse. The total energy on the target was 12 J, and the energy ratio of these pulses was 1 : 4, respectively. The pulse separation was 2.0 ns, and each duration were 400 ps and 7 ps, respectively. The spectral profile of the XRL was measured by a high-resolution spectrometer, HIREFS made by Hettrick scientific [6]. The entrance slit position was 70 mm from the edge of the plasma. The far field image of the XRL on the slit was relayed to the detector position. The back-illuminated CCD (Princeton, PI-SX:1K) was used for the detector. The inverse linear dispersion of the spectrometer was determined by use of carbon Balmer α line (182.20 Å) and Ni-like Mo XRL line (188.95 Å) [9]. The inverse linear dispersion was 785 mÅ /mm on the CCD surface. This value together with the information of CCD pixel size, slit size (= 3 μm) and magnification of HIREFS (= 3.2) led to the resolution of the total system of 12.7 mÅ ($d\lambda / \lambda = 7 \times 10^{-5}$).

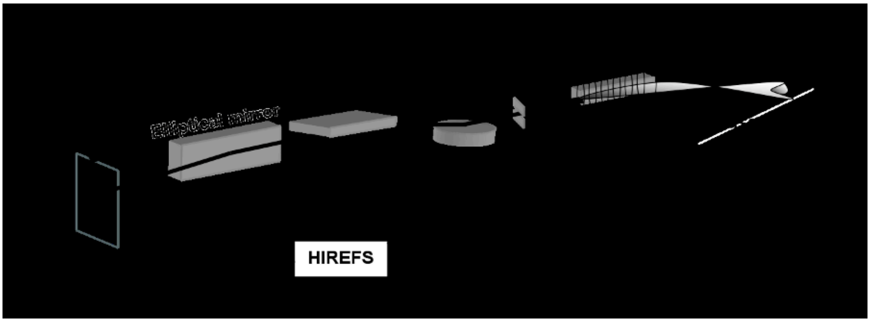

Fig. 5 Experimental setup for the extraction of the circularly polarized XRL.

Figure 6 (i) shows the obtained spectra of the Ni-like Mo XRL without and with the external magnetic field, respectively. As the difference between these spectra was clearly seen, and apparent split of the spectrum was obtained under the presence of the magnetic field.

Fig 6 (ii) shows the spectral profile of the XRL under the magnetic field. The notation (a),..(e) corresponds to the position in Fig. 6 (i). As the refraction angle increases, the separation becomes larger. If the separation of the spectrum was decided due to only the Zeeman effect, the strength of the magnetic field near the target surface was higher than that far from the target surface. The strength of the magnetic field in the gain medium estimated to be (a) 41, (b) 122, (c) 179, (d) 218, (e) 270 T at each position, and these quantities were quite higher compared with the expected external magnetic field. It implies that there might be alternative mechanism for enhancement of the magnetic field in plasma, such as the spatial compression of the magnetic flux due to the shock wave [10] occurred when the main pulse of the pumping laser was incident to the XRL medium. The detail of the mechanism is under consideration now.

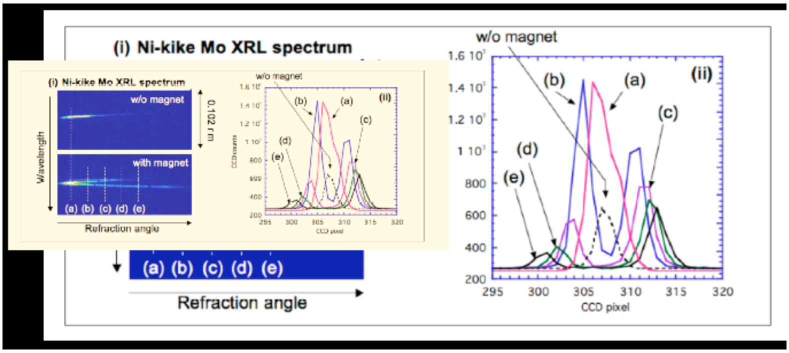

Fig. 6 (i) XRL spectra without and with the external magnetic field. (ii) Cross section of the XRL spectrum.

4 Summary

We proposed the method of the extraction of the circularly polarized XRL using the external magnetic field. From the measurement of the spectral width of the Ni-like Mo XRL (~ 0.002 nm), we estimated that magnetic field of ~ 45 T is required for the complete separation of the circular polarization components. Preliminary experiment was conducted under external magnetic field (~ 20 T), and the separation of the XRL line was obtained.

The estimated strength of the magnetic field from the split value of the spectrum of the XRL was quite higher than the expected value. This result implied there was alternative mechanism for enhancement of the magnetic field in plasma, such as the spatial compression of the magnetic flux due to the shock wave.

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