X-RAY LASING AND HARMONIC GENERATION IN TRANSIENT GAIN SCHEME OF LONGITUDINALLY PUMPED Ni-LIKE Mo PLASMA

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Abstract

We present our studies on the generation of coherent soft-x-ray radiation using hybrid tabletop Ti:sapphire – Nd:glass femtosecond laser. Longitudinally pumped collisional excitation of Ni-like Mo ions was used for x-ray lasing (λ = 18.9 nm). X-ray laser radiation has shown possessing the small angular distribution and strong dependence on delay between picosecond and femtosecond pumped radiation.

1. Introduction

X-ray lasers with transient gain schemes are of great interest during last time because of their compactness, high brightness and robustness. Various schemes were proposed for generation of coherent soft-x-ray radiation in the wavelength range of tens nanometers [1-4]. Their potential applications are the high-density plasma probing, microscopy of biological tissue, etc. [5,6]. The advantage of the proposed schemes respectively to previously reported laser-pumped x-ray lasers is due to small pumping energy of fundamental radiation.

Below we present our studies on amplification of soft x-ray at 18.9 nm in Ni-like Mo plasma using proposed early [7] longitudinally pumping geometry. The condition of the pre-plasma produced by the picosecond long pulse is calculated using the HYADES code, which is a one-dimensional, three-temperature Lagrangian hydrodynamics and energy transport code. Radiative energy transport is treated in a multigroup prescription, the degree of ionization is determined by the Thomas-Fermi model, and the equation of state quantities are derived from realistic tables. The target geometry and plasma expansion is assumed to be planar. The interaction of the femtosecond short laser pulse with the preformed plasma is calculated using a code based on the hot-spot model. A compact collisional-radiative model is used to model the atomic kinetics, and gain is calculated from the distribution of the excited state population.

2. Experimental setup

A long pulse (300-ps) and a short pulse (475-fs) beams from a tabletop, 1.06-μm hybrid Nd:glass – Ti:sappire CPA laser [8] were sent into the target chamber (Fig. 1). The long pulse was focused onto the Mo target to form 100 μm × 2 mm line focus, while the short pulse was send through the laser-produced plasma in rectangular direction. The beam waist size and confocal parameter of the femtosecond radiation were 30 μm and 10 mm respectively. The intensities of the long and short pulses were 1.5×10^{11} and 3×10^{16} W cm^{-2} respectively.

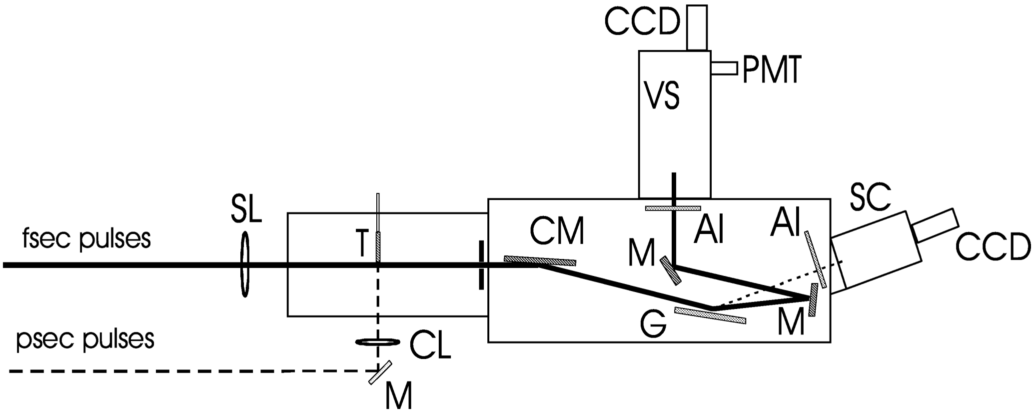

Fig. 1. Experimental setup. SL: spherical lens; M: mirrors; CL: cylindrical lens; T: target; CM: cylindrical mirror; G: grating; VS: vacuum spectrograph; CCD: CCD cameras; SC: streak camera; PMT: photomultiplier tube; Al: aluminum filters.

The IR and X-ray radiation were propagated through the slit of X-ray spectrometer consisting of gold-coated cylindrical mirror and 1200 grooves/mm grating in the grazing incidence scheme ($\alpha=87^o$). The x-ray streak camera (Hamamatsu C1936) was placed at the position of the first order diffraction of 19 nm radiation. Zero-order reflection from the grating was sent to the vacuum spectrograph (Acton VM504) and the signals from the laser plasma were registered both by CCD camera and photomultiplier (Hamamatsu R2496) with sodium salicylate layer.

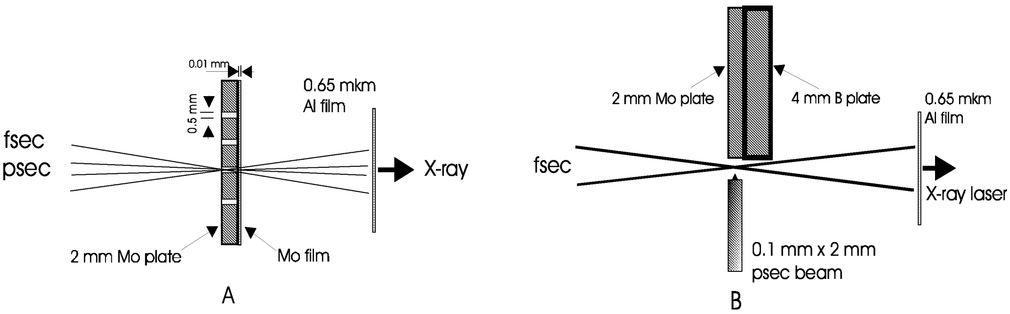

Fig. 2. Target set-up. A - longitudinally pre-pumped scheme; B - transversally pre-pumped scheme.

We used two geometries of targets (see Fig. 2). In the first case (rectangular propagation of long and short pulses) we were able to change the distance between the target and femtosecond radiation focal point. For calibration of x-ray spectrometer and streak camera we used boron target placed at the position close to the molybdenum plate. The thickness of Mo plate was 2 mm. In the second case (parallel propagation of the beams) we used 0.01 mm thick Mo foil attached to the 2-mm thick Mo plate with 0.5 mm holes.

3. Results and discussion

Our first studies were performed with the prolonged Mo plasma (Fig. 2B). We investigated the dependences of 18.9-nm radiation on intensity of femtosecond radiation and delay between picosecond and femtosecond radiation. Fig. 3 shows the spectrum of x-ray laser and boron plasma in the vicinity of 19 nm. The spectra of Mo plasma dominated by the $3d^9 4d\,^1S_0 \rightarrow 3d^9 4p\,^1P_1$ laser line of 18.9 nm. Our estimations of angular characteristics of x-ray laser radiation have shown that the last not surpass 5×10^{-3} rad.

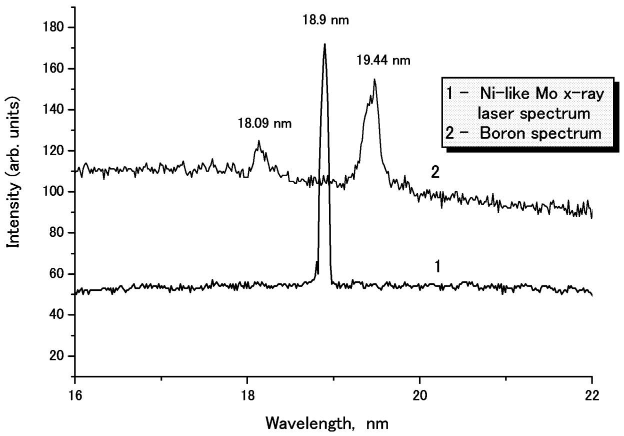

Fig. 3. Spectrum of the Ni-like molybdenum X-ray laser spectrum around 19 nm. The boron spectra of third-order 6.03 nm and fourth-order 4.86 nm resonant lines are presented for comparison.

The dependence between the x-ray laser intensity and fundamental intensity is presented in Fig. 4. It is not possible to reach the conclusion about whether or not we had unsaturated regime of 18.9-nm radiation lasing since saturation has to do with gain, and not the x-ray intensity. Since spontaneous emission intensity is proportional to the upper laser level density, and since the x-ray intensity is a factor of spontaneous emission intensity and the amplification factor, we cannot know how the change in the laser intensity changed the x-ray laser intensity, unless further investigations are performed.

The intensity of the x-ray laser radiation essentially depended on the delay between the long and short pumped pulses. Maximal signal was registered at 4-ns delay. Increasing the delay longer than 10-ns led to the disappearance of lasing at this wavelength.

We analyzed various parameters' dependencies on that process. Ratio between the heating pulses' energies ($k=E_{fs}/E_{ps}$) has changed from 1 to 10. The optimal conditions were found to be at k=4. Another important parameter is the distance between the target and focal point of femtosecond radiation. The maximal signal was registered at the distance of 0.2 – 0.3 mm from the Mo surface.

Our preliminary results on heating of the Mo foil (Fig. 2A) have not shown generation of coherent x-ray radiation. Laser plasma obviously was too thick that prevented the optimal conditions of x-ray lasing. Broadband spectrum of plasma radiation detected by vacuum spectrograph had continuum radiation in visible and ultraviolet ranges. Insertion of the photomultiplier tube PMT and 0.65 μm thick Al filter instead of the vacuum spectrograph has shown the strong signal 8 ns before the plasma-induced signal in the range of transmittance of the filter. The odd-harmonic generation in laser plasma (13th and above) can be the source of this signal besides the 18.9-nm radiation. Further studies on spectral distribution of VUV radiation are necessary for detailed analysis of nonlinearities of pre-heated plasma.

Using the HYADES code, the density and temperature of the pre-plasma is calculated to be 4×10^{19} cm^{-3} and 20 eV, respectively. We assume an initial nickel-like ion abundance of 40 %, and that the rest of the ions are in the copper-like stage. For a main pulse intensity of 3×10^{16} W cm^{-2} and a temporal duration of 475 fs (FWHM), taken from the present experimental conditions, the 18.9 nm gain coefficient reaches a maximum of 13 cm^{-1} at a time 1.8 ps after the peak of the main pulse. Considering the 2 mm length of the molybdenum target, the resulting gain-length product is less than 3. Although actual gain measurements have not been performed, this value is too small considering that the 18.9 nm line completely dominates the spectrum in Fig. 3. A possible cause for this discrepancy may be that the pre-plasma also expands in the axial direction, increasing the length of the gain region.

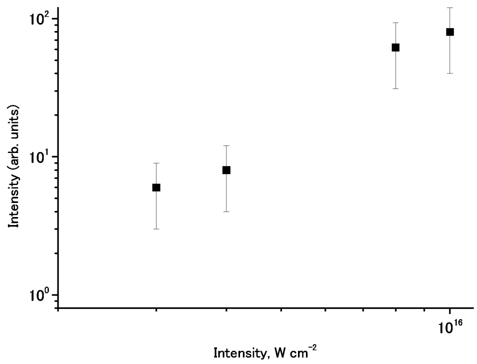

Fig. 4. 18.9 nm radiation intensity as a function of femtosecond radiation intensity

4. Conclusion

In conclusion, x-ray laser (18.9 nm) generation studies of longitudinally pumped Ni-like molybdenum plasma were presented. It was shown that proposed scheme improved pumping efficiency and overcame various limitations of present transient gain lasers. Various experimental conditions were investigated and dependences of the x-ray intensity on parameters of experiments (delay time, heating pulses' ratio, IR laser intensity, etc.) were presented. We have demonstrated the high brightness of the tabletop x-ray laser. We compare our experimental results on generation of 18.9 nm radiation with theoretical predictions.

Acknowledgments

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