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Sub-milliradian Divergence 18.9 nm Ni-like Mo Plasma Soft X-ray Laser Pumped by Transient Collisional Excitation with Subpicosecond 150 mJ Laser

H. Kuroda, A. Ishizawa[1]*, R.A. Ganeev**, M. Baba, M. Turu, S. Sakakibara, T. Kanai, and T. Ozaki[1]

Institute for Solid State Physics, University of Tokyo,
5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan
[1] NTT Basic Research Laboratories, NTT Corporation,
3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan

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.

Introduction

Transient-collision-excitation x-ray lasers have received much interest due to the relatively compact pump source required, compared with quasi-steady state collisional excitation systems [1,2]. Their potential applications include high-density plasma probing and microscopy of biological tissue [3,4]. In this work we present our studies on amplification of soft x-ray at 18.9 nm in Ni-like Mo plasma using previously proposed longitudinally pumping geometry [5]. Our laser pumping system consists of low-energy picosecond pre-heating pulses and low-energy femtosecond heating pulses with overall energy around 150 mJ. To our knowledge it is the smallest energy level of pumping radiation at which the coherent lasing in the range of 19 nm using transient collisional excitation scheme was obtained.

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* Presently with NTT Basic Research Laboratories
** Present address : NPO Akadempribor, Academy of Sciences of Uzbekistan, Tashkent 700143, Uzbekistan

Experimental Setup

Long-pulse (300 ps) and short pulse (475 fs) beams from a tabletop, 1.06-µm hybrid Nd:glass – Ti:sappire chirped pulse amplification (CPA) laser operated at the Institute for Solid State Physics of the University of Tokyo [6] were sent into the target chamber (Fig.1). The long pulse was focused onto the Mo target to form 100 µm × 3 mm line focus, while the short pulse was sent through the laser-produced plasma from a longitudinal direction. The beam waist size and confocal parameter of the femtosecond radiation were 30 µm and 10 mm, respectively. We monitored laser parameters including energy, pulse delay and spectrum. The laser was fired once per 5 min. The intensities of the long and short pulses were 10^{13} and 10^{16} W cm^{-2} respectively.

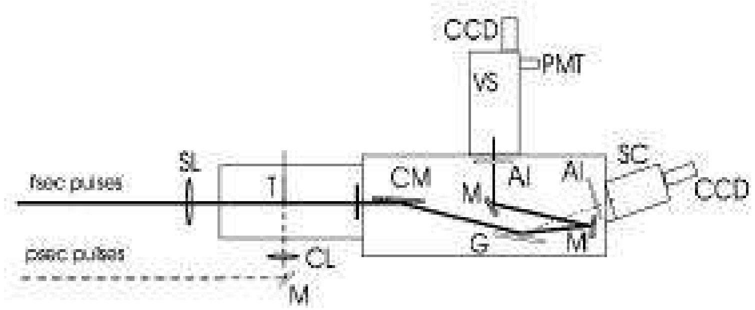

Fig. 1. Experimental setup. SL: spherical lens; M: mirrors; CL: cylindrical lens; T: target; CM: cylindrical mirror; G: grating; VS: vacuum spectrograph; CCD: CCD cameras; SC: streak camera; PMT: photomultiplier tube; Al: aluminum filters

The on-axis x-ray radiation was directed through the slit of a flat-field x-ray spectrograph consisting of gold-coated cylindrical mirror and 1200 lines/mm Hitachi grating. The spectrally diffracted beam was sent to the x-ray photocathode camera (Hamamatsu C1936) with gold-polymer photocathode and sensitivity in the area around 100 eV and 10 keV. The time-integrated spectrum was registered by CCD camera (Hamamatsu 5575). Zero-order reflection from the grating could also be sent to a vacuum spectrograph (Acton VM504). We used either a CCD camera (Hamamatsu C4880) or a photomultiplier tube (Hamamatsu R2496) with sodium salicylate window to register the spectrally dispersed signal from the laser plasma. 0.65 µm thick Al filter was used for both zero- and first-order diffracted beams.

Slab molybdenum targets were used in this experiment. We varied the distance between the target surface and femtosecond radiation focal point. For calibration of x-ray spectrograph and streak camera we used boron target placed at the position close to the molybdenum plate. The length of molybdenum plate was 2 mm. We changed the delay between long and short pulses from 0 to 10 ns.

Experimental Results

We investigated the dependence of 18.9-nm radiation on intensity of femtosecond radiation and delay between picosecond and femtosecond radiation. Fig.2 shows the spectrum of x-ray laser in the

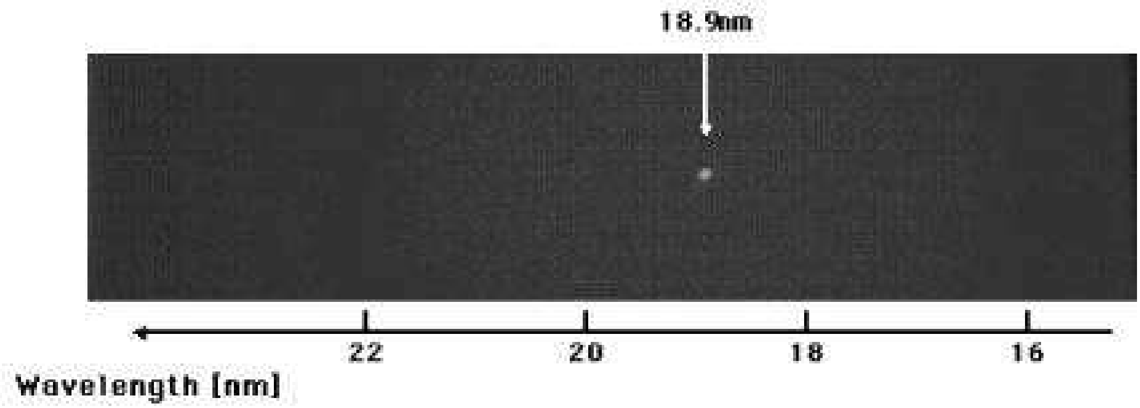

Fig. 2. On-axis spectrum from molybdenum plasma in the vicinity of 19 nm.

vicinity of 19 nm. One can see that the $3d^94d^1S_o \rightarrow 3d^94p^1P_1$ laser line at 18.9 nm dominates the spectrum from the molybdenum plasma. Our estimations of angular characteristics of x-ray laser radiation have shown a divergence of the x-ray laser to be 0.34 mad.

The dependence between the x-ray laser intensity and fundamental intensity is presented in Fig.3. This dependence indicates an unsaturated regime of 18.9-nm radiation lasing. The intensity of the x-ray laser radiation also depended on the delay between the long and short pumped pulses. Maximal signal was registered for 4-ns delay. Increasing the delay longer than 10-ns led to the disappearance of lasing at this wavelength.

We analyzed the dependence of lasing on various parameters. Ratio between the energies of the heating pulses ($k = E_{fs} / E_{ps}$) was varied 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 0.1 mm from the molybdenum surface.

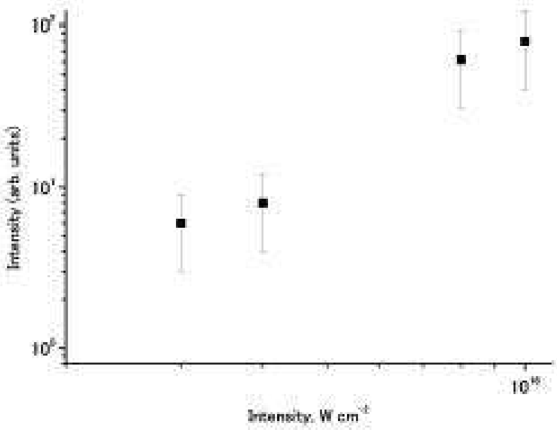

Fig. 3. Intensity of 18.9 nm line as a function of the femtosecond laser intensity.

Discussion

The measured sub-milliradian divergence of the 18.9 nm x-ray laser is extremely small, considering that short 2-mm-long plasma gain medium was used. If geometrical optics is assumed, the transverse size of the gain region must be several μm to realize such small divergence, which is unrealistic. We have performed detailed simulations of our experiment, and have found that the 1×10^{-5} contrast ratio pedestal of the longitudinal pump beam produces a unique electron density and gain profile. These profiles closely resemble the parabolic profiles used in the works of London et al. [7]. For such cases, refractive antiguiding of the x-ray laser beam will result in the selective amplification of the lowest-order transverse modes. This explains the high spatial coherence of our x-ray laser.

Conclusions

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. We took into account the nonlinear response of the plasma and theoretically analyzed various medium lengths responsible for accumulation of soft x-ray amplification. 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.

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