*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, O-1.008 (2005)*

# Brilliant Highly Directive Higher Harmonics and Soft X-Ray Lasers from Solid Target Plasma Pumped by Tabletop Ti:S Laser

H. Kuroda[1], R. A. Ganeev[1], M. Suzuki[1], M. Baba[1], J. Zhang[1], and T. Ozaki[2]

[1] *The Institute for Solid State Physics, The University of Tokyo*

*5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan*

[2] *Institut national de la recherche scientifique 1650 boul. Lionel-Boulet*

*Varennes (Quebec) Canada J3X 1S2*

## 1. Introduction

The high-order harmonic generation (HHG) in visible and extreme ultraviolet (XUV) ranges has been investigated in the laser plasma formed by optical breakdown in gases and at the surface of solid targets (see [1] and references therein). In this paper we demonstrate the efficient generation of coherent XUV radiation after the propagation of femtosecond pulse through the low-excited plasma produced on the surface of different solid targets. The harmonics up to the 65$^{th}$ order and the conversion efficiencies up to $8\times10^{-5}$ were achieved in these studies. Strong resonance enhancement of single harmonic will also be discussed.

## 2. Experimental arrangements

The pump laser used in this research was consisted of chirped-pulse amplification Ti:sapphire laser, whose output was further amplified using a three-pass amplifier. A portion of uncompressed radiation ($E$=15 mJ, $t$=210 ps, $\lambda$=796 nm) was split from the main beam by a beam splitter and used as a prepulse. This prepulse was focused by a spherical lens on a solid target located in the vacuum chamber and produced a plume predominantly consisting on neutrals and singly charged ions [2]. The intensity of picosecond prepulse, $I_{pp}$, on the target surface was varied between $7\times10^9$ W cm$^{-2}$ to $8\times10^{10}$ W cm$^{-2}$. After some delay, the femtosecond main pulse ($E$=8 mJ, $t$=150 fs, $\lambda$=796 nm) was focused on the target plasma from the orthogonal direction using 200-mm or 100-mm focal length lenses. Our experiments were carried out up the maximum intensity of the femtosecond main pulse of $I_{fp}=1\times10^{15}$ W cm$^{-2}$.

The high-order harmonics were analyzed by a flat-field grazing-incidence XUV spectrometer with a Hitachi 1200-groove/mm grating [4]. An additional gold-coated grazing-incidence cylindrical mirror was used for the image translation from the plasma area to the detector. The XUV spectrum was detected by a microchannel plate with phosphor screen and recorded by a CCD camera.

## 3. Results and discussion

We used different solid targets (Ag, B, In, C, W, Se, Mo, Nb, Si, Zr, Mg, Cd, Pd, Al, Cr, Ta) for the preparation of suitable laser plumes for our experiments. The choice of targets was stipulated by our aim to analyze the influence of atomic number, ionization potentials, and other parameters of samples on the HHG from different plumes.

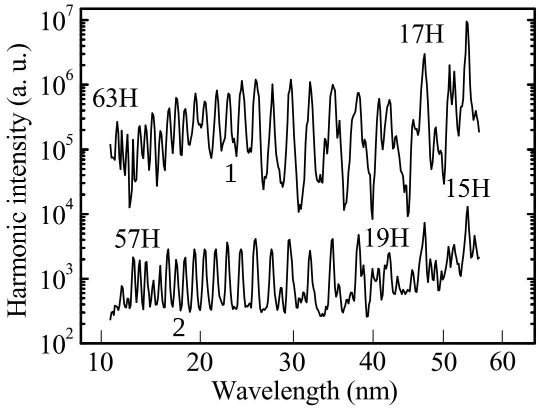


Fig. 1. Harmonic output as a function of the wavelength of generated XUV radiation in the cases of (1) orthogonal and (2) longitudinal pump schemes.

The plateau pattern of high-order harmonic distribution was appeared in these experiments. In particular, high harmonics up to the 63rd order at a wavelength of 12.6 nm were observed in experiments with boron plasma at loosely focused conditions ($b$=6 mm, $L_p$=0.6 mm, $L_p$ is the plasma sizes). The HHG from the B plume appeared to be similar to those observed in gas-jet experiments, with characteristic shape of plateau for the harmonics exceeding 17th order (Fig. 1, curve 1). Higher harmonics (up to the 65th order, $\lambda$=12.24 nm) were observed at the conditions when the confocal parameter of focused radiation was changed ($b$=1.2 mm) to be close to the plasma sizes.

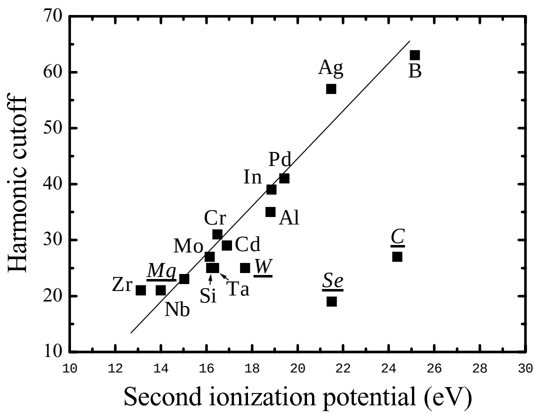


Fig. 2. Dependence between the cutoff harmonic and ionisation potential of ions (second ionisation potential) for different targets. The plateau pattern was not observed in the cases of C, Se, W, and Mg plumes.

Analogous pattern was appeared in the case of longitudinal scheme, when femtosecond beam propagated through the laser plasma and hole drilled in the target [3]. High harmonics up to the 57th order ($\lambda$=13.96 nm) were routinely observed in these experiments (Fig. 1, curve 2).

The plateau pattern was appeared in the case of the HHG from most of plasma samples used in these experiments, while in some cases (W, C, Mg, Se) we observed a steady or even steep decrease of conversion efficiency for each next harmonic. We observed a direct relation between the cutoff energy of the harmonics generated from different targets and the second ionisation potential of atoms. Figure 2 shows a linear dependence between these two parameters in the case of the targets where we observed a plateau pattern. These observations underline a decisive role of free electrons appearing during further ionisation of singly charged particles that led to the restriction of cutoff energy. The conversion efficiencies in the plateau region were varied between $10^{-7}$ to $8\times10^{-6}$ depending on the target.

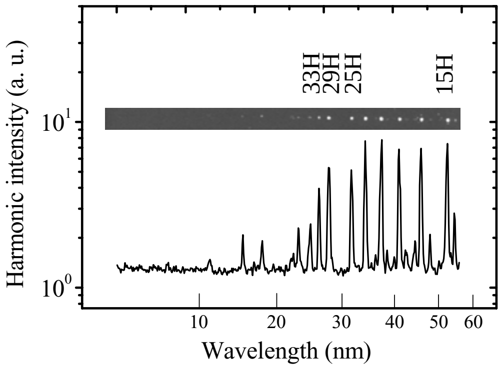


Fig. 3. Harmonic spectrum from chromium plasma in XUV range.

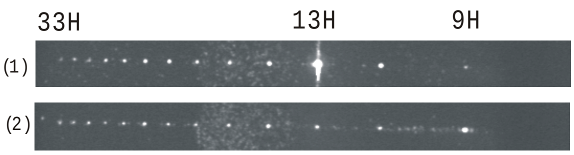


Fig. 4. High-order harmonic spectra from (1) indium and (2) silver plumes.

While most of targets showed a prolonged plateau-like distribution of high harmonics, some of them demonstrated very interesting features that were not observed previously in gas-jet experiments. In particular, in the case of chromium plasma we registered a considerable suppression of 27$^{th}$ harmonic with comparing to the neighbour harmonics (Fig. 3). Such a feature was observed in the cases of different focusing geometries using both 200-mm and 100-mm focal length lenses. The absence of 27$^{th}$ harmonic was registered in a broad range of main pulse intensities.

Most intriguing pattern was appeared in the case of indium plasma. We observed anomalously strong 13$^{th}$ harmonic radiation ($\lambda$=61.2 nm), which almost two orders of magnitude exceeded the neighbour ones (Fig. 4). These studies were repeated using different focusing conditions and plasma geometries. The conversion efficiency of 13$^{th}$ harmonic was measured to be $8\times10^{-5}$.

An enhancement of HHG efficiency should include the optimisation of both macroscopic and microscopic responses. From the macroscopic point of view, such an optimisation dominantly means an achievement of ideal phase matching conditions.

Microscopic optimisation includes the methods of the growth of polarization of harmonics that depends on nonlinear susceptibility of a separate harmonic. The last parameter considerably depends on the relation between the excited states of nonlinear medium in the vicinity of harmonic wavelength. To our opinion, the strong $13^{th}$ harmonic was a result of resonance-induced enhancement of nonlinear susceptibility in the vicinity of 61 nm.

## 4. Conclusions

In conclusion, we demonstrated the generation of high harmonics (up to $65^{th}$ order, $\lambda$=12.24 nm) after the propagation of femtosecond laser pulses through the low-excited surface plasma created by a prepulse radiation. High-order harmonics generated from most plumes showed a plateau pattern. The harmonic generation in these conditions assumed to occur due to the interaction of femtosecond pulses with ions. The conversion efficiency for the harmonics generated in the plateau region was varied in the range of $10^{-7}$ to $8\times10^{-6}$ depending on target. The main contribution to the limitation of harmonic generation efficiency was caused by free-electrons-induced self-defocusing of main beam.

Our observation of the considerable resonance-induced enhancement of a single harmonic ($\lambda$=61.2 nm) in the plateau region with the efficiency of $8\times10^{-5}$ in the case of In plume can offer some expectation that analogous processes can be realized in other plasma samples even in the shorter wavelength range where the highest harmonics were achieved. It is difficult to realize this approach in gas puffs due to the necessity of the preparation of specific conditions for the excitation of appropriate levels of nonlinear medium prior to laser-matter interaction.

## References

1. C.-G. Wahlström, S. Borgström, J. Larsson, S.-G. Pettersson, Phys. Rev. A 51, 585 (1995).
2. R. A. Ganeev, I. A. Kulagin, M. Suzuki, M. Baba, H. Kuroda, Opt. Commun. 249, 310 (2005).