Generation of high intensity XUV radiation by high-order harmonics and its application

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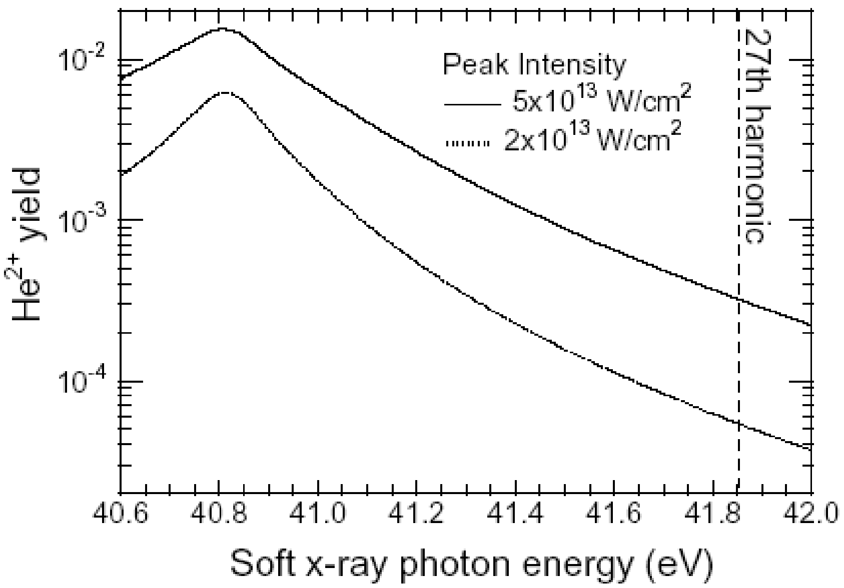
The advent of ultrashort high-peak power lasers enables us to investigate a variety of phenomena of high-filed interaction with atom or molecules. High-order harmonic generation (HHG) is one of such interesting phenomena. HHG can produce ultrashort coherent extremely ultraviolet (EUV) pulses from a compact laser system. This emission source is useful for EUV nonlinear optics, attosecond physics, and EUV spectroscopy.

However, an output energy of HHG was limited by low conversion efficiency and low input energy. In order to increase the output energy to a micro-joule level, 5-m long loose focusing pumping geometry was newly designed to deliver several tens mJ pump pulses into a 100-mm-long interaction cell, keeping phase-matched conditions. With this geometry, we have generated an output energy of 0.33 μJ at the 27th harmonic with an efficiency of 1.5×10^{-5} with a perfect beam quality [1]. From the measured beam parameters for the 27th harmonic, the peak brightness of this coherent soft X-ray can be estimated to be 8×10^{26} photons/mm^2/mrad^2/s, assuming a beam diameter of 60 μm at the exit of the gas cell.

By changing an active medium from 10 cm, 2 Torr Ar to 14 cm, 0.6 Torr Xe, an output energy has been increased by more than ten-fold at wavelengths between 73.6 to 42.6 nm [2]. From the relative harmonic strength distribution, the maximal XUV light energy was estimated to be 7 μJ for the 11th harmonic (72.7nm), 4.7 μJ for the 13th harmonic (62.3 nm), and 1 μJ for the 15th harmonic (54 nm). The peak power of the 13th harmonics was estimated to be 0.13 GW, assuming the same pulse width as the pump of 35 fs. The peak brightness of this low-emittance 62.3 nm light was estimated to be 3×10^{28} photon/mm^2/mrad^2/s with a measured beam divergence of 0.5 mrad. The average brightness of this coherent EUV light is comparable to that of synchrotron orbit radiation despite a low repetition rate of 10 Hz.

When we focus these harmonic beams with a 10-cm-radius concave multilayer mirror, the focused intensity reaches $>10^{14}$ W/cm^2. This high field is expected to boost nonlinear optics in the EUV region.

Fig. 1 shows numerical simulations of two-photon ionization of He^+ by 27th harmonic pulses of a Ti:Sapphire laser [3]. This process is chosen as a candidate for the experimental observation of a nonlinear optical effect in the soft x-ray domain. We solve the time-dependent Schrödinger equation and evaluate the ionization probability as the number of electrons absorbed by the mask function at the outer radial boundary. Our model can address questions concerning possible saturation and quantum interference in ionization at high intensity and ultrashort pulseduration with no unambiguity. According to our results, in spite of saturation of ionization found at intensity higher than 10^{13}W=cm^2, the ionization probability by a 30 fs harmonic pulse with a peak intensity of 2 to 5×10^{13} W=cm^2, attainable with latest progress in high-order harmonic generation, should be sufficiently high to put the second-order nonlinear optical process in the soft x-ray region within experimental reach, along with desirable properties such as its nearly quadratic dependence on intensity and approximate linearity in pulse width.



Fig, 1. The yield of He^{2+} as a function of photon energy of a gaussian pulse with a duration of 30 fs. The solid and dotted lines correspond to peak intensity I = 5 x 10^{13} W/cm^2 and 2 x 10^{13} W/cm^2, respectively.

References

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