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Observation of Burst Intensification by Singularity Emitting Radiation generated from relativistic plasma with a high-intensity laser

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ABSTRACT

Coherent x-rays via the Burst Intensification by Singularity Emitting Radiation (BISER) mechanism are generated from relativistic plasma in helium gas target. A broad modulation of the BISER spectrum, which is significantly wider than the harmonic order, is observed and characterized. In particular, we found that the modulation period can be as large as 41 eV.

1. Introduction

High-power laser and plasma interactions produce particle beams and electromagnetic waves such as high-energy ions, high-energy electrons, and high-order harmonics [1–4]. High-order harmonics have been observed in the relativistic regime with solid [5–8] and gas [9–11] targets. In the case of a solid density target, the models of harmonic generation in the relativistic regime include the relativistic oscillating mirror [4,12,13] and sliding mirror [14,15]. In a gas target, Burst Intensification by Singularity Emitting Radiation (BISER) is observed [9–11]. The BISER is a new mechanism of harmonic generation by oscillating electron spikes at the joint of the wake wave and bow wave [16] boundaries. These electron density spikes (singularities) generate the bright coherent x-rays. The electron density spikes are off-axis and therefore produce harmonics with both even and odd orders having the same shape and intensity. In this experiment, we observe the BISER spectra with a helium gas target irradiated with a high-intensity laser. The modulations of the BISER spectra are observed and characterized.

2. Experimental setup

The J-KAREN laser system [17,18] is used as a high-intensity laser. Fig. 1 shows the experimental setup. The typical laser power is ~10 TW and central wavelength is ~820 nm. The laser pulse is focused by an off-axis parabolic mirror (f/9) and the estimated peak intensity is $>10^{18}$ W/cm^2. The linearly polarized laser pulse has been focused into a helium gas jet streamed from a conical nozzle. The laser power in vacuum exceeds the critical power of the relativistic self-focusing [19]. Thus, the laser pulses self-focus during propagation in plasma and acquire higher irradiance than in vacuum. To reduce the noise caused by bremsstrahlung x-rays, high-energy electrons are deflected from the forward direction by permanent magnets. The transmitted optical spectra are observed with a fiber spectrometer (Ocean Optics: HR2000) with a calibrated relative spectral sensitivity. The BISER spectra generated from relativistic plasma in the forward direction are measured by a grazing-incidence flat-field spectrograph, comprised of a gold-coated collection mirror, spherical varied-line-space grating, and back-

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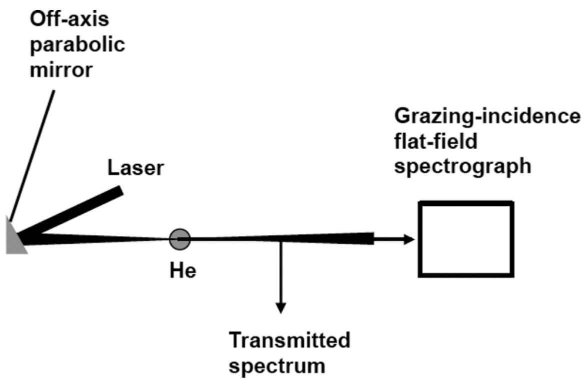

Fig. 1. Schematic diagram of the experimental setup.

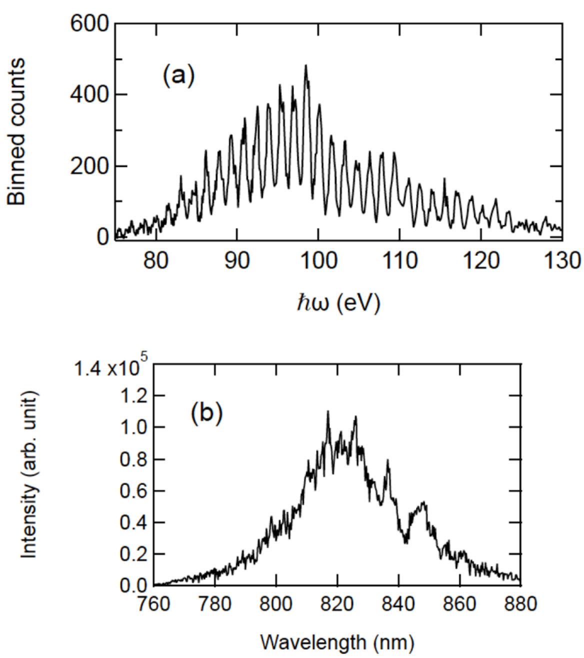

Fig. 2. Typical high order harmonic spectrum (a), and transmitted optical spectrum (b) at the laser power of ~8 TW. The electron density of He plasma is ~4.7 × 10^{19} cm^{-3}.

illuminated CCD camera [9,10]. Bright spots in some spectra caused by the hard x-rays are removed by the procedure described in the Appendix A of Ref. [23].

3. Experimental results

Fig. 2(a) shows the typical BISER spectrum at the laser power of ~8 TW. The horizontal axis is the photon energy and the vertical axis is the binned counts of the CCD pixels. The electron density of the He plasma is ~4.7 × 10^{19} cm^{-3}. The BISER spectra contain even- and odd-order harmonics. The base harmonic frequency of this spectrum is 1.55 eV, which corresponds to the wavelength of 800 nm. Fig 2(b) shows the transmitted optical spectrum. The base frequency of the high order harmonics corresponds to the wavelength of 800 nm, which is within the original laser bandwidth but somewhat shorter than the central wavelength.

Along with the optical-frequency (~1 eV) modulation, the BISER spectra often contain much broader (~10 eV or so) modulations. Such modulations obtained in separate laser shots are shown in Fig. 3 (a–d); here the modulation period varies due to both different experimental parameters and shot-to-shot fluctuations. The electron densities in these shots ranged from ~4.7 × 10^{19} cm^{-3} to ~7.1 × 10^{19} cm^{-3} and laser power from ~6 to ~11 TW. The jumps of spectra around 100 eV correspond to the silicon L absorption edge. The modulation periods in the photon energy domain are (a) 6.2 eV, (b) 16 eV, (c) 26 eV, and (d) 41 eV. These values have been determined by the Fourier Transform of the experimental spectra, Fig. 3 (e–h). The accurate spectral calibration of the spectrograph ensured high precision of the obtained modulation periods.

The deep large-scale modulations seen in these spectra suggest that those modulations result from interference between two coherent sources separated in time and/or space. The time difference between these two pulses can be calculated from the modulation period as $\Delta t = 2\pi\hbar/\Delta E$. The calculated time difference, Δt, vs. modulation period, ΔE, is shown in Fig. 4 by the solid line. The circles are the measured modulation periods in individual shots. The maximum time difference is Δt = 1.9 fs at ΔE = 2.1 eV and the minimum time difference is Δt = 0.1 fs at ΔE = 41 eV. Even larger-period modulations, and correspondingly shorter time separations, could in principle be generated in the experiment, but those could not be observed due to the limited spectrograph bandwidth.

4. Discussion

The two coherent pulses which cause the observed modulations can be generated either by two spatially separated sources characteristic to the BISER mechanism in the case of a linearly polarized driver pulse ([11], Figs. 1 and 3) or by each source emitting double pulses during each period, which is seen in simulations ([11], Figs. 2d and 4). In the case of the double BISER source, the distance difference (and the corresponding time difference) between each of the point sources and the spectrometer makes the spectral modulations. For example, the time differences of 0.1 fs and 1.9 fs can be explained by the 0.29° and 5.5° tilts of the two individual sources relative to the observation direction. The separation between these two individual sources of 12 μm is assumed here [11]. A possible reason for this tilt is the nonlinear hosing instability [20–22].

5. Summary

We have observed and characterized broad spectral modulations in the BISER spectra generated by a high-intensity laser in a helium gas target. The measured spectral modulation period ranges from 2.1 eV to 41 eV, which is much wider than the harmonic order separation (~1 eV). These broad spectral modulations are attributed to the interference of coherent pulses separated in time. The reasons for these pulse generation are briefly discussed.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

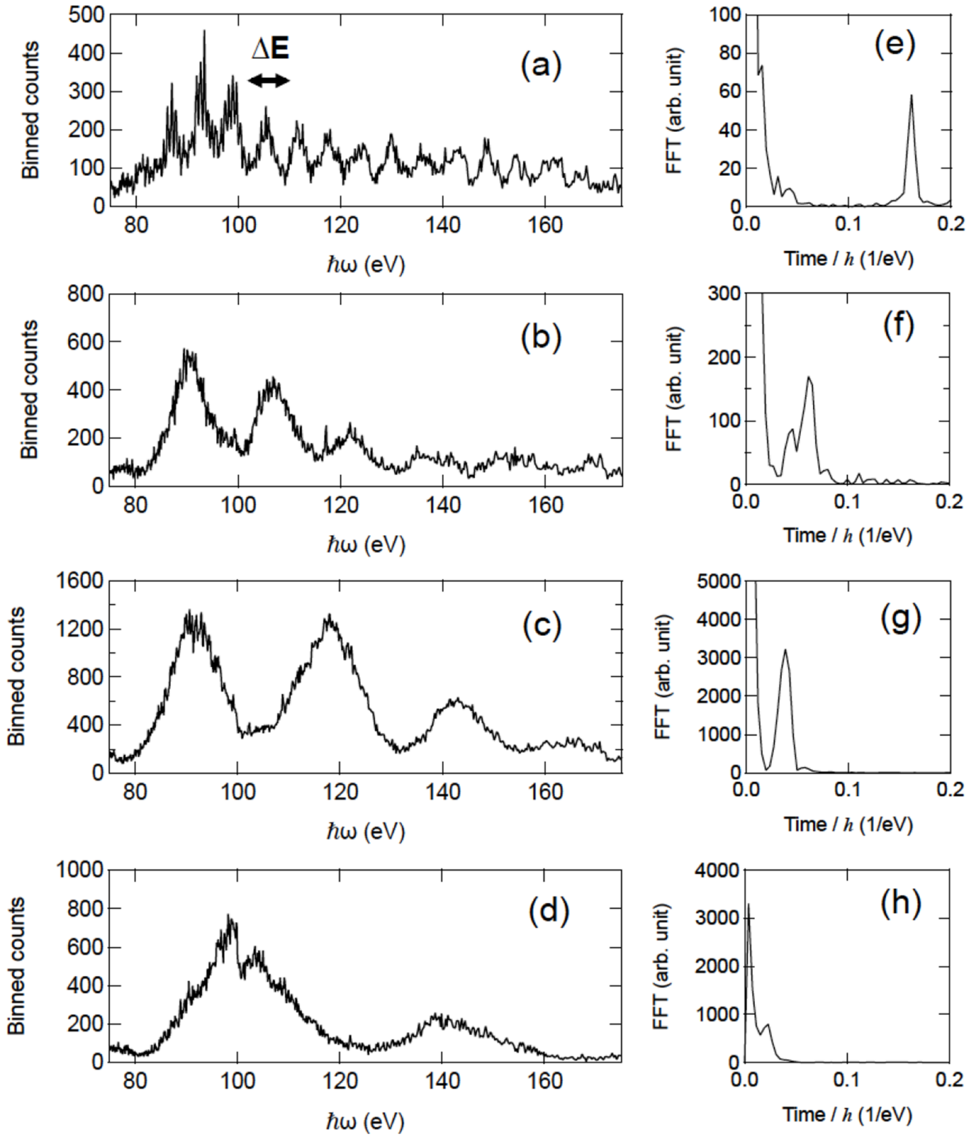

Fig. 3. High order harmonic spectra with the broad modulations. The modulation periods in the photon energy domain are (a) 6.2 eV, (b) 16 eV, (c) 26 eV, and (d) 41 eV. The right panels (e–h) show the Fourier Transforms of the experimental spectra; here the horizontal axis is time/*h*, where *h* is the Planck's constant.

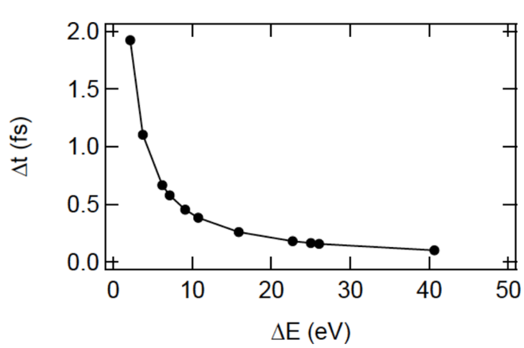

Fig. 4. Calculated time difference vs. energy width of the spectral modulations.

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