Construction of a Magnetic Bottle Electron Spectrometer for Electron Energy Measurement in BISER X-Rays and Xe Interaction*)

Hikari OHIRO, Alexander S. PIROZHKOV[1)], Koichi OGURA[1)], Akito SAGISAKA[1)], Tatiana A. PIKUZ[2,3)], Kai HUANG[1)], Masaki KANDO[1)], Kotaro YAMASAKI and Shinichi NAMBA

Department of Advanced Science and Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-hiroshima, Hiroshima 739-8527, Japan

[1)]*Kansai Photon Science Institute, National Institutes for Quantum Science and Technology (QST), 8-1-7 Umemidai, Kizugawa, Kyoto 619-0215, Japan*

[2)]*Institute for Open and Transdisciplinary Research Initiatives, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan*

[3)]*Joint Institute for High Temperatures of the Russian Academy of Science, Izhorskaja Street 13/19, Moscow 127412, Russia*

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Quantum science and technology Kansai group has found new harmonics X-ray radiation from the relativistic laser-produced plasma, burst intensification by singularity emitting radiation (BISER). As a next step, the BISER pulse width is one of the unclear parameters, and its measurement is essential for applications of BISER to scientific and engineering fields. Therefore, we designed and constructed a magnetic bottle time-of-flight electron spectrometer to characterize the BISER pulse width using a pump-probe method (attosecond streaking). The spectrometer configuration was determined through numerical calculations to obtain a high-energy resolution of approximately 0.2 eV. The electron spectra of the xenon atom irradiated with the BISER X-rays were measured to verify the performance. Consequently, we successfully measured 8.26-eV Auger spectra associated with 4*d* inner-shell electrons in the test experiment. We demonstrate the experimental results and discuss the signal-to-noise ratio affected by electromagnetic noise generated by the relativistic plasma.

Keywords: BISER, pump-probe method, magnetic bottle time-of-flight electron spectrometer, mirror magnetic field, Auger electron

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1. Introduction

Recently, Pirozhkov *et al.* of quantum science and technology (QST) Kansai group observed a new harmonics radiation emitted from the relativistic laser-produced plasma [1–3]. This is called burst intensification by singularity emitting radiation (BISER). It produces odd harmonics with respect to fundamental frequency, in contrast to the conventional atomic harmonics (only odd harmonics emission due to inversion symmetry of rare gases). Particle-in-cell simulation showed that X-rays have a duration of 170 as. The X-ray radiation mechanism is explained by the localization of relativistic electrons (singularity) [1–3]. Our research aims to measure the BISER pulse width using a pump-probe technique (attosecond streaking) [4–6]. In this pump-probe method, the electron is ionized by a pump attosecond X-ray pulse (BISER), and simultaneously, the electron emitted is exposed (dressed) by the femtosecond IR probe pulse. The energy of the dressed electron changes depending on the incident timing of the pump pulse and phase of the probe pulse. The extra IR photon is absorbed or emitted according to the phase of the probe pulse. Thus, with varying the temporal overlap of both pulses with a very fine step, one can evaluate the pulse duration of the pump attosecond X-rays [4–7]. To this end, an electron spectrometer that can measure electron spectra with a high-energy resolution is required to observe the attosecond X-ray pulse width. Therefore, we constructed a high-energy resolution magnetic bottle time-of-flight (TOF) electron spectrometer.

The advantages of the TOF type spectrometer are as follows: (1) simple structure compared with a concentric hemispherical analyzer and cylindrical mirror analyzer [8, 9], (2) large collection angle (almost 4π), (3) high-detection efficiency up to 100% for low-energy electrons, and (4) measurement of energy spectra in a single

author's e-mail: m215659@hiroshima-u.ac.jp

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shot. Therefore, to design and construct the spectrometer, we calculated electron trajectories in a magnetic field formed by a permanent magnet and a solenoid coil and a detection efficiency using a finite-element method. The actual energy resolution of the spectrometer is determined by measuring xenon 8.26-eV Auger electrons generated by $4d$ inner-shell decay associated with the xenon atom subjected to the BISER X-rays above a photon energy of 69 eV and by fitting spectral data with Gaussian profile. For attosecond BISER X-ray pulse width measurements, xenon 8.26-eV Auger electrons were observed. It is worth noting that the Auger electron spectra have specific energy peaks regardless of the incident X-ray photon energy. Meanwhile, various photoelectrons were created due to many order harmonics of the BISER. The energy resolution required is approximately 0.2 eV. The construction of the magnetic bottle TOF electron spectrometer and a series of experiments have been conducted at Hiroshima University and QST Kansai facility, respectively.

2. Design of a Magnetic Bottle Electron Spectrometer

Figure 1 (a) shows a schematic of the magnetic bottle TOF spectrometer. The magnetic mirror field was generated by a taper-shaped permanent magnet and solenoid. The field strength of the permanent magnet (made of neodymium with a diameter of 30 mm, a length of 30 mm, and a taper angle of 110°) was 1.0 T at the taper tip (z = 30 mm). A weak uniform field of 1.0 mT was applied by the solenoid coil that was wound on a 145-mm diameter stainless steel tube. The wire diameter was 2.4 mm (made of 2.0-mm copper with an outer insulator that was 0.4 mm thick), and the field length was 1.2 m (with 500 turns). The coil current was 2 A. The magnetic field outside the vacuum tube was shielded by a nanocrystalline soft magnetic material of 20-μm thickness (FINEMET; Hitachi Metal). A microchannel plate (MCP, F9892-11; Hamamatsu Photonics) with an effective diameter of 42 mm was located 1.2-m away from the BISER focal point. The MCP rise time was 1.2 ns.

The electrons were generated at 2.0-mm downstream from the permanent magnet, where xenon atoms were irradiated with the focused BISER X-ray pulses. Almost all electrons could reach the detector guided by the magnetic mirror field. We conducted a numerical calculation using a finite-element method to calculate the magnetic field in the TOF tube. Figure 1 (b) shows the plot of the field strength rA_θ (i.e., the stream function) generated by the magnet and solenoid, where r is the radius, and A_θ is the vector potential (axial symmetry). As shown in this figure, a smooth magnetic mirror field was formed in the flight tube. The trajectory of electrons in the field was calculated by solving the equation of motion. Here 8.26-eV electron kinetic energy was assumed. The electrons guided by the mirror field reached the MCP detector, as shown in Fig. 1 (b).

Figure 2 shows the plots of the spatial electron distribution at the MCP detector (xy projection) when 2500 electrons were randomly emitted into 4π direction from the 500-μm spherical spot at the focal position indicated by the black circle. The influence of the space charge on electron energy was not considered. The electrons were guided into the effective area of the detector, and their spatial spread by the red circle was within a diameter of 15 mm. The MCP size of 42 mm was sufficiently large to detect all electrons.

Figure 3 shows the electron energy distribution at the focal position and calculated one at the MCP detector. The electron energy is converted from electron flight time. The Auger peak energy and energy bin are 8.26 and 0.02 eV, respectively. Consequently, the electron energy distribution at the MCP position is shifted to the lower energy side because the actual electron trajectory follows Larmor motion. Its travel length becomes longer than that without a magnetic field. Additionally, the detection position at the MCP

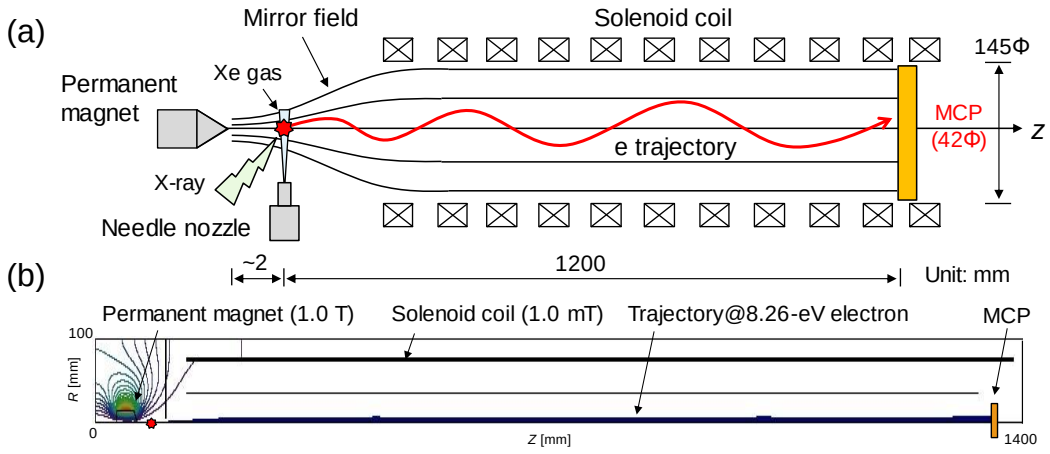

Fig. 1 (a) Schematic of the magnetic bottle TOF electron spectrometer. (b) Plot of the stream function $rA\theta$ of the magnetic field and electron trajectories calculated using a finite-element method.

changes depending on the direction emitted from the focal point, as shown in Fig. 2. Thus, narrowing the detection region will improve the energy resolution.

3. A Test Experiment to Measure Electron Spectra Ionized by BISER Radiation

Figure 4 shows a schematic of the electron spectrometer constructed consisting of an interaction chamber and a 1.2-m long TOF tube. A permanent magnet, a 0.25-mm diameter needle nozzle, and a 3.0-mm aperture were installed in the interaction chamber. The permanent magnet and needle nozzle were mounted on *xyz* stages. The BISER beam coming from the bottom was focused and steered by a pair of X-ray mirrors, interacting with xenon gas target (gas pressure of 1.0×10^{-3} Pa) introduced from the needle nozzle through a variable leak valve, as shown in Fig. 4. A 200-nm Zr thin filter was installed to block out-of-band radiation; a double-pass 120-nm thick $Zr/ZrSi_2$ multilayer filter was installed in front of the focusing mirror to protect from laser light. The MCP was located 1.2 m away from the BISER focal point. An X-ray CCD camera was installed at the top port to take alignment images of the BISER X-ray beam passing through the interaction zone. Two turbo-molecular pumps evacuated the interaction chamber and TOF tube. The relative positions of the focal point, permanent magnet, and gas feeding needle were precisely adjusted. Additionally, the BISER X-rays irradiated into the interaction zone were aligned near a tip end of the gas nozzle and the magnet by a shadow graph, as shown in Fig. 5.

We used an ultra-intense Ti:Sapphire laser (J-KAREN-P at QST [10, 11]) to generate BISER. The laser parameters were as follows. The estimated peak power was 17 TW; the vacuum laser intensity was 5×10^{18} W/cm^2, whereas the intensity in plasma was several times higher due to relativistic self-focusing. The central laser wavelength was 795 nm; the effective laser spot radius in Ref. [10] was 11 μm, whereas the repetition rate was 0.1 Hz. BISER was generated using a similar setup reported in Ref. [3]. The BISER radiation was focused by a spherical multilayer X-ray mirror (f = 375 mm) with a magnification of 9 and steered to the xenon gas by a flat multilayer mirror. We used two filters (one in double pass and another in single pass) to block IR and visible radiation. After in-

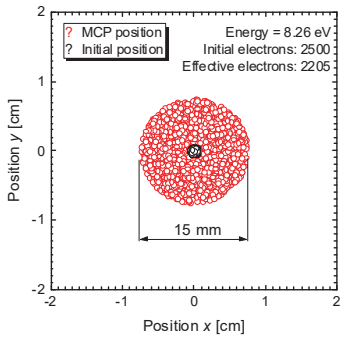

Fig. 2 Spatial distribution of electrons at the MCP detector (red circle). The electrons have a kinetic energy of 8.26 eV; initially, 2500 particles are randomly emitted from a 500-μm sphere (black circle).

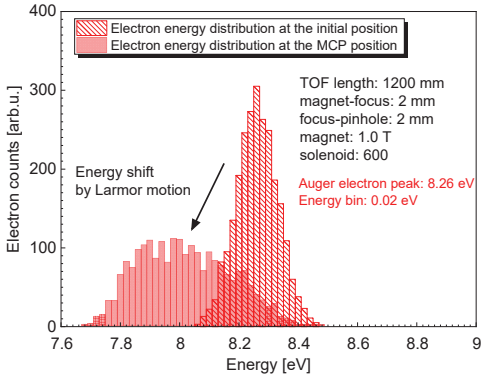

Fig. 3 Electron energy distribution at the MCP position. The Auger electron peak energy is 8.26 eV; energy bin is 0.02 eV.

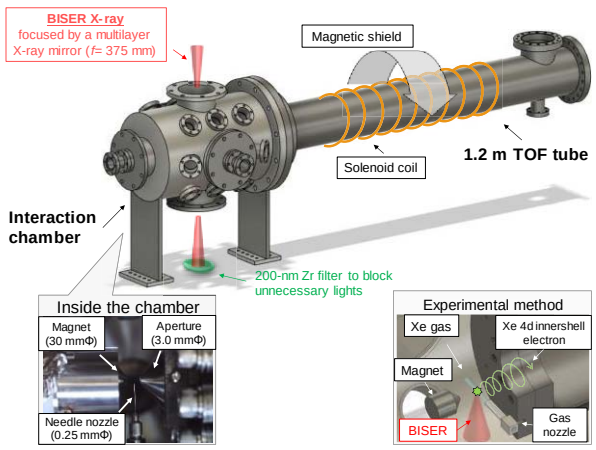

Fig. 4 Schematic diagram of the magnetic bottle electron spectrometer and detailed configurations of each component.

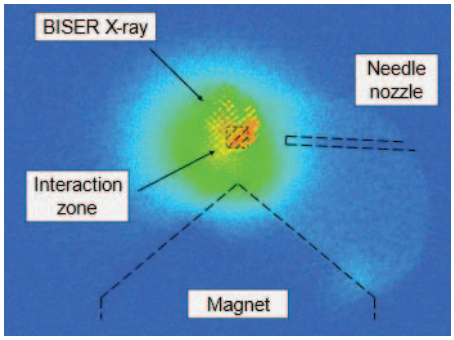

Fig. 5 Typical CCD image of the BISER X-rays taken from the top port.

teraction with Xe, the BISER radiation diverged and propagated to alignment X-ray CCD, where its spot size was approximately 2.5 mm. The total pulse energy evaluated from the CCD count was 6.2 pJ.

4. Results and Discussion

Figure 6 shows the typical TOF spectra measured in the BISER X-ray and xenon interaction. The horizontal axis corresponds to the flight time, and the vertical axis is the MCP signal. The black curve is the background data, and the red one is the experimental data. The spectra are integrated by 14 shots with a similar BISER intensity. Note that we have been unable to count accurately the number of electrons generated due to large noise. One can see significant noise in the time range of 0 - 300 ns. Thus, the 300 - 900 ns signal is considered valid for evaluating the TOF spectra. This time window corresponds to the electron energy range of 5 - 40 eV.

The conversion from the flight time to electron energy spectra is expressed by

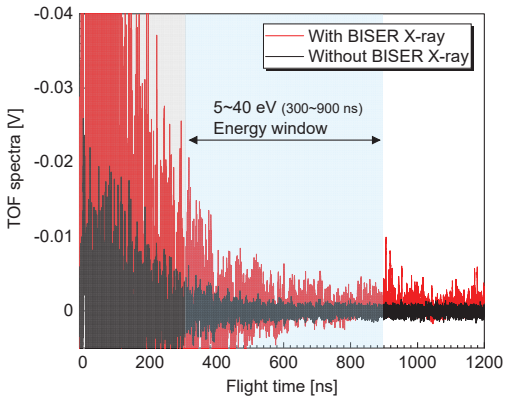

Fig. 6 Typical TOF spectra measured in the BISER X-rays and xenon interaction.

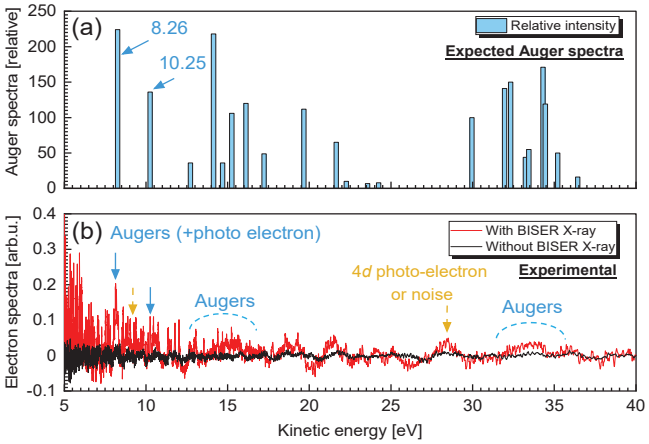

Fig. 7 (a) Relative Auger electron intensity. (b) Electron spectra measured in BISER and xenon gas interaction.

$$g(E) = \left(-\frac{et^3}{m_e l^2}\right) f(t), \tag{1}$$

where e is the electronic charge; t is the flight time; m_e is the mass of electron; l is the TOF length; $f(t)$ is the MCP output voltage. Figure 7 (b) shows the energy spectra determined from Eq. (1). Figure 7 (a) shows a relative Auger electron intensity. Comparing Figs. 7 (a) and (b), we can see that the Auger spectrum is observed at approximately 8.26 and 10.25 eV. The 8.26-eV Auger spectrum is the most intense in this spectral window.

The signal-to-noise (S/N) ratio was quite low because the large noise was generated by the electromagnetic wave emitted from the relativistic plasma and the instantaneous change of the ground potential. The low S/N is also attributed to the insufficient BISER pulse energy. This is because the reflectivities of both X-ray mirrors used were as low as approximately 10% - 20% at 13.9-nm wavelength, around which an ionization cross-section of xenon 4*d* inner electrons is as large as 16 Mb [12]. Consequently, the X-ray beamline throughput (with the filters) was approximately 0.005. The signal will become higher using an appropriate pair of multilayer X-ray mirrors with higher reflectivities. For the next experiments, we prepare focusing and plane Mo/Si multilayer mirrors with high reflectivities of more than 60% at a wavelength of 13.9 nm.

5. Summary

We have designed and constructed a magnetic bottle TOF electron spectrometer. We used the BISER X-rays as an X-ray source to evaluate the spectrometer's performance. Consequently, we observed the xenon Auger electron spectra at approximately 8.26 eV, although the electron spectra suffered from significant noise. We plan to use a pair of specially designed Mo/Si multilayer mirrors to increase BISER X-ray intensity at the focal point and resultant Auger electron number and improve the S/N ratio in the next experiments.

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