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High resolution electron spectrometers for characterizing the contrast of isolated 25 as pulses

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ABSTRACT

We quantify the effects of the energy resolution of a magnetic bottle electron spectrometer in an attosecond streak camera on the accuracy of measuring the relative amplitudes of satellite pulses around the main attosecond pulse. Our numerical simulations show that the spectral resolution can be significantly improved by restricting the acceptance angle using a pinhole located near the source of the photoelectrons. The intensity of the pre- and post-pulses which are 1% and 10% of a main 25 as pulse can potentially be measured with less than 10% error by two practical time-of-flight spectrometer designs.

1. Introduction

When an isolated attosecond light pulse is generated from a gas medium driven by an intense femtosecond laser, the main pulse is always accompanied by pre- and post-pulses, usually referred to as satellite pulses, regardless of the gating technique used [1–3]. Since attosecond pump-attosecond probe experiments for studying electron dynamics require minimum disturbance of the system before and after the main pulse, the intensity of the satellite pulses should be 10% or less of the primary pulse. The contrast of the attosecond extreme ultraviolet (XUV) pulses can be retrieved from attosecond streaking traces [4]. Previously, experimental defects that affect the satellite pulse retrieval have been discussed for pulses longer than 80 as in [5–9]. However, the effect of the spectrometer resolution, which is of critical importance for characterizing a broadband XUV pulse, has not been discussed in detail. In this report, we studied the effects of the energy resolution of the electron spectrometer on the accurate characterization of the pre- and post-pulses surrounding a 25 as main pulse, which corresponds to one atomic unit of time. Briefly, the current experimental setup is discussed in Section 2. The resolution of the spectrometer is numerically evaluated in Section 3. Two methods to improve the energy resolution are discussed in Section 4 and the performance on satellite pulse retrieval of the new designs is shown in Section 5.

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2. Current setup

We consider an attosecond streak camera based on a magnetic bottle electron spectrometer (MBES) as shown in Fig. 1, with which 67 as pulses were recently demonstrated [10]. This type of time-of-flight (TOF) spectrometer is chosen because of its high collection efficiency and high energy resolution [11–13]. The details of the spectrometer have been described elsewhere [14]. Briefly, a rare earth magnet (NdFeB) and a conical pole piece made of soft iron create a 0.8 Tesla magnetic field at the surface of the pole piece. A gas jet with 50 μm inner diameter is located 1 mm away from the tip of the pole piece, where the XUV pulse is focused to produce photoelectrons from the target atoms. A solenoid coil is wrapped around the 3 m long flight tube to generate 10 Gauss magnetic field, and a microchannel plate (MCP) detector is mounted at the end of the flight tube to record the photoelectron signal. The photoelectrons enter the fight tube through an aperture with a diameter D, which was designed for differential pumping. The diameter of the aperture is 1 mm, much large than the electron beam diameter there. Fig. 1(b) shows the enlarged diagram of the magnet and aperture with the photoelectron angular distribution.

3. MBES resolution and satellite pulse retrieval

To evaluate the energy resolution of the MBES, the electron trajectories and their flight times are traced by numerical simulations [15]. As shown in Fig. 2(a) for a monoenergetic source of 180 eV electrons, the energy calculated from the flight time depends on

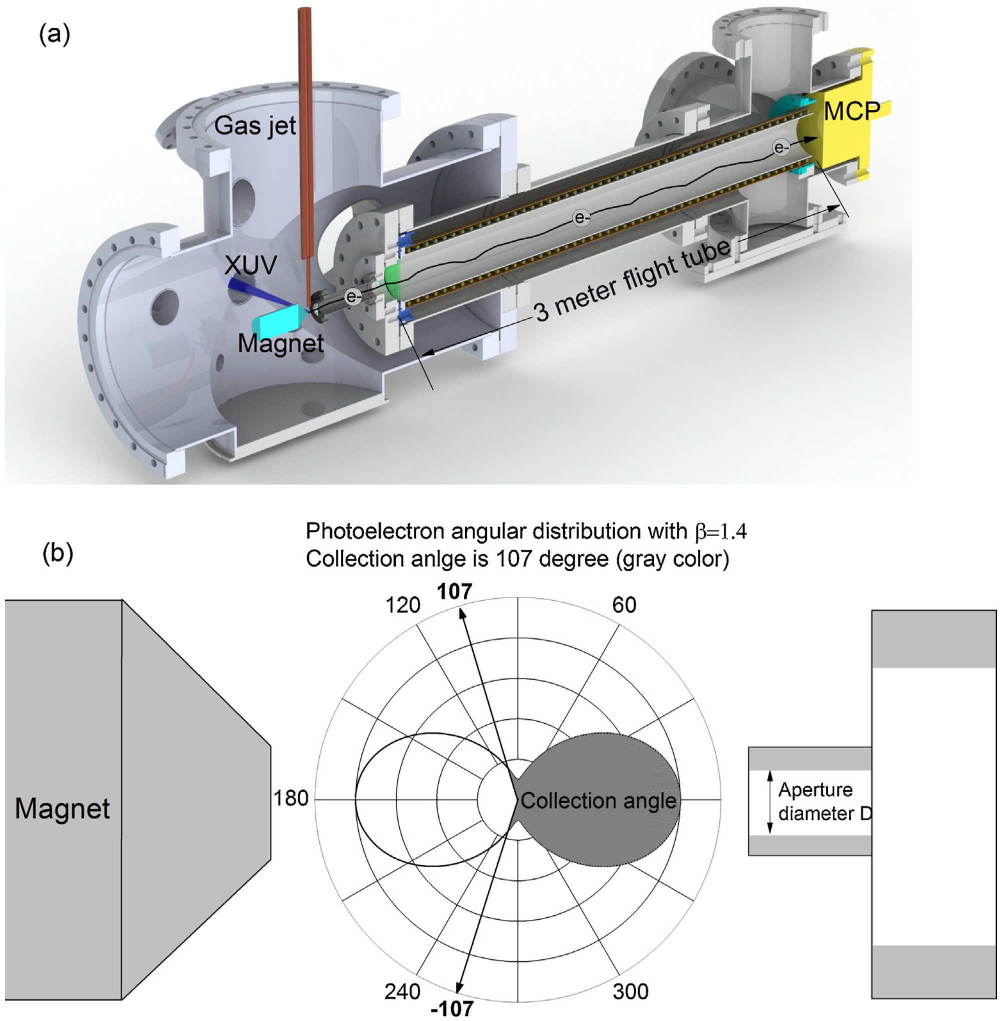

Fig. 1. (a) Diagram of magnetic bottle electron spectrometer (MBES) with a 3 m long flight tube. The XUV beam is focused at 1 mm away from the magnet which produces a highly diverging magnetic field and a 50 μm diameter stainless steel gas jet is placed on top of the XUV beam. Photoelectrons enter an aperture with a diameter D and fly through the 3 m long tube before reaching the MCP detector. A solenoid coil with 0.8 A current is wrapped around the flight tube to supply a 10 Gauss magnetic field. A μ-metal tube is placed outside the flight tube to shield the earth magnetic field. (b) An enlarged schematic diagram of the magnet and aperture. The plot in polar coordinates shows the photoelectron angular distribution with an asymmetry of 1.4. The collection angle of the MBES is calculated to be 107°. The solid angle within which the photoelectrons can be collected by the MBES is shown in gray color.

the emission angle of the photoelectron relative to the axis of the flight tube. This energy should be regarded as the "TOF energy", which is different from the true initial kinetic energy of the photoelectrons. The larger the emission angle, the more the TOF energy deviates from the true value. For electrons emitted at 107°, which is the largest accepting angle of the current setup as shown in Fig. 1(b), the difference between the two values reaches 1.8% for a 3 m long TOF.

The angular distribution of the photoelectrons from a given target atom is given by:

$$\frac{d\sigma}{d\Omega} \propto 1 + \frac{\beta}{2}[3\cos^2(\theta) - 1], \qquad (1)$$

where $d\sigma/d\Omega$ is the differential photoionization cross section, θ is the emission angle, and β is the asymmetry [16]. Neon is used in the simulations due to its large photoionization cross section and nearly constant β value for energies above 40 eV [16]. Using the above equation and the results shown in Fig. 2(a), we plot in Fig. 2(b) the TOF energy distribution of monoenergetic 180 eV electrons with all possible emission angles, which is referred to as the "response function" of the MBES. The long tail in the low energy part of the response function results from electrons with large emission angles. We note that with this unique distribution, it is not appropriate to define the energy resolution by the full-width-at-half-maximum (FWHM) because it does not reflect the contribution of the long tail.

To study the effect of the MBES resolution on the satellite pulse retrieval, we use a 25 as transform-limited (TL) Gaussian pulse, with central photon energy at 151 eV. It has pre- and post-pulses with 1% intensity contrast to the main pulse. The satellite pulses have 50 as pulse duration with the same central photon energy and are ±2500 as away from the main pulse, as depicted in Fig. 3(a). The spacing equals to one optical period of the driving laser centered at 750 nm, which is typical for the Double Optical Gating [3]. The corresponding photoelectron spectrum is shown with black solid line in Fig. 3(b), which spans from 30 to 220 eV.

The red dashed line in Fig. 3(b) represents the energy spectrum after convoluting the real spectrum with the MBES response function calculated with the 3 m flight tube. The response function was normalized to its area before the convolution to ensure the equal weight for all energies. A streaking spectrogram is then generated numerically with the XUV pulse and a 5 fs, 750 nm near infrared (NIR) streaking pulse which has a peak intensity of 5×10^{11} W/cm^2. The spectrum in each delay in the streaking